Geologic Description, Sampling, Petroleum Potential, and Depositional Environment of the Chuar Group, Grand Canyon, Arizona

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Abstract

In October 1996, two stratigraphic sections of the Late Proterozoic Chuar Group located in the Nankoweap Canyon and Carbon Canyon areas of the eastern Grand Canyon National Park, Arizona, were measured, described, and sampled. The goals of the study were to: (1) characterize the petroleum reservoir and source rock potential and depositional environment of the full section from the Proterozoic Nankoweap through Cambrian Tapeats Formations, and (2) establish a reference sample collection at the Arizona Geological Survey for future study. In the Nankoweap Canyon area, 3799 ft of section were measured and described and 133 samples were collected. In the Carbon Canyon area, 4935 ft of section were measured and described and 169 samples were collected. A total of 8734 ft of section was measured and 302 samples were collected.

Forty-seven samples were analyzed for reservoir characteristics and 258 samples were analyzed for source rock potential. All 258 of the source-rock samples were analyzed for total organic carbon (TOC), and all 65 samples with TOC's of 0.5% or greater were run for Rock-Eval pyrolysis. Thirty-one of the 65 samples were chosen for organic petrographic study. The stratigraphic thicknesses measured in this study are compared to previous studies.

Only the 887 ft Walcott Member and the upper 165 to 390 ft of the Awatubi Member consistently have a TOC content of fair or better and it is only these 2 units that constitute the significant source rock potential of the Chuar Group. The Tmax maturity gradient of these 2 units ranges from immature at the top to late oil window at the base of the organically rich Awatubi in the Nankoweap Canyon area (NCA) and both intervals are entirely immature in the Carbon Canyon area (CCA). The NCA maturity gradient, therefore, appears to be slightly higher than that of the CCA. The apparent difference may be due to (1) a deeper or longer burial associated with the Late Precambrian extensional tectonism (Grand Canyon disturbance) and erosion (Great Unconformity) or the late Mesozoic - early Tertiary Laramide orogeny, or (2) a higher heat flow associated with any of the 3 periods of volcanism and plutonism ranging from the Cretaceous Period through the Quaternary Epoch. Alternatively, the difference may only be an artifact, due to a higher average Walcott maturity than average Awatubi maturity, skewing the gradient higher in the NCA, or due to the margin of measurement error on the few Galeros data points in the 2 areas. It is unclear why the average Walcott maturity is higher than the average Awatubi maturity in the NCA.

In 22 of the 31 samples (71%) studied petrographically, the Tmax maturity was lower than all of the organic petrologic maturity indicators: (1) vitrinite reflectance equivalent (VRE), (2) bitumen Ro, (3) vitrinite-like ("other") Ro, (4) thermal alteration index (TAI), and (5) fluorescence extinction. Either the organic petrologic indicators are correct and Tmax is underestimating maturity, or Tmax is correct and weathering or other causes have produced an apparent increase in the maturity of the organic petrology indicators. Moderate to strong iron oxide alteration may have caused elevated TAI values. Alternatively, since

maturation is a function of both time and temperature, the higher effective maturity indicated by the organic petrology may have been achieved at the lower than usual Tmax temperatures during the extra 235 million years the Chuar source rocks have been maturing relative to the usual Phanerozoic (543 million years or younger) source rocks.

Based on the petrologic maturity indicators, most NCA Walcott samples seem to be in the peak oil to condensate/wet gas windows. On the same basis, the rich NCA Awatubi samples are mostly in the peak oil to condensate/wet gas windows and the rich CCA Awatubi samples are mostly in the immature to condensate/wet gas windows.

Stable carbon isotope data suggest that the Tanner, Carbon Canyon, Awatubi, and Walcott Member shales are marine in origin, allowing the possibility of widespread original deposition. Four wells with Precambrian sediments are known from southern Utah and northern Arizona. The geometry of Precambrian preservational basins is unknown, but if the half graben structural pattern seen in the Grand Canyon is widespread, the Chuar Group may be widely preserved on the fault-bounded, downthrown edge of these rotated half graben.

A productivity index (transformation ratio) of less than 0.3 for all points except 1, indicates a maturity of immature or oil window and that the hydrocarbons are indigenous to the source rocks analyzed. A cross plot of reactive carbon index (RCI) vs. productivity index (PI) indicates Chuar points plot in the gas prone and uncertain area.

Unstructured kerogen (lipids) makes up most of the organic matter in all samples. Minor amounts up to 15%, but generally trace amounts, of vitrinite-like organic matter and solid bitumen also occur. The solid organic matter had little or no fluorescence and with 1 exception, the TAI was uniformly 3 or 3 to 3+.

Introduction

In October 1996, two stratigraphic sections of the Late Proterozoic Chuar Group were measured, described, and sampled in eastern Grand Canyon, Arizona (Figure 1). The northern section was located in the Nankoweap Canyon area (Figure 2). The southern section was located in the Carbon Canyon area (Figure 3). The goal of the study was to characterize the petroleum reservoir and source rock potential and depositional environment of the full section of strata from the Late Proterozoic Nankoweap through Cambrian Tapeats Formations (Table 1). In the Nankoweap Canyon area, 3799 ft of section were measured and described and 133 samples were collected. In the Carbon Canyon area, 4935 ft of section were measured and described and 169 samples were collected. A total of 8734 ft of section was measured and 302 samples were collected.

About 1/2 of each sample was analyzed for petroleum reservoir and/or petroleum source rock potential. A total of 47 samples were analyzed for reservoir characteristics by Core Laboratories, Inc. of Midland, Texas. Reservoir sample analysis included permeability, porosity, and grain density. A total of 258 samples were analyzed geochemically for source rock potential by DGSI of The Woodlands, Texas, as a subcontractor of Baseline Resolution, Inc. of Plano, Texas. All 258 of these samples were analyzed for total organic carbon (TOC) as a measure of organic richness, and the 65 samples with TOC yields of 0.5 wt % or greater were run for Rock-Eval pyrolysis which included Tmax as a measure of thermal maturity. Based on these results, 31 samples were chosen for organic petrographic study. Tables 2 and 3 summarize the analytical results for the 2 sections. The details of these analytical results are plotted on Plates 1 and 2 beside of each of the measured sections and are included in Appendix 1 in tabular form. Field notes of the study are recorded in Appendix 2.

The remaining 1/2 of each sample has been deposited with the Arizona Geological Survey, forming a collection available for future study of outcrops which are relatively remote, as well as difficult and expensive to access. The full analytical results of this study are available for review in 6 volumes at the Arizona Geological Survey. These are: Volume 1 - Screening Analyses, Volume 2 - Extract GC, Volume 3 - Saturate GC/MS, Volume 4 - Saturate GC/MS, Volume 5 - Aromatic GC/MS, and Volume 6 - Aromatic GC/MS.

Previous Work and Evolution of a Petroleum Play Concept

For excellent reviews of the development of the Grand Canyon Proterozoic and Cambrian stratigraphic nomenclature the reader is referred to Beus and Morales (1990), Rauzi (1990), Ford and Breed (1973), Elston and others (1989), and Cook (1991). The current Chuar Group stratigraphic terminology is essentially that of Ford and Breed (1973) who measured and mapped the Chuar Group and subdivided it into 3 formations [Sixtymile Formation was subsequently removed from the Chuar Group by Elston and McKee (1982)] and 7 members (Table 1). Their mapping, as slightly modified by Ford (1990, p. 50, Figure

1) was the mapping used in the present study. The present study supplemented these 2 maps with that of Huntoon and others (1996) especially with respect to some of the structural features mapped and the Tapeats mapping. Ford (1990) reviews the correlation, environment of deposition, and paleontology of the Nankoweap Formation and Chuar Group.

For reviews of the Tapeats stratigraphy, depositional environment, and paleontology see Middleton and Elliot (1990), McKee and Resser (1945), Hereford (1977), Beus and Billingsley (1989), and Elston (1989).

The high organic richness in portions of the Chuar was noted by Bloeser and others (1977), who calculated that a shale horizon in the Walcott Member of the Kwagunt Formation contained about 10,000 microfossils per cubic centimeter. Vidal and Ford (1985) reported that microfossils were abundant to common throughout the dark mudstones and siltstones of the Chuar Group. In 1986 Reynolds and Elston (1986, Abstract) described abundant microfossils and organic material in the dark mudstones and siltstones of portions of the Chuar Group and suggested deposition in a sediment-starved lacustrine environment.

The petroleum source rock potential of portions of the Chuar Group was explicitly recognized in 1988 by Summons and others (1988) and Reynolds and others (1988, Abstract). Summons and others (1988) studied kerogen from the bituminous and argillaceous dolomite of the Walcott Member and identified this as Type I-II kerogen in the mature region of the Van Krevelen diagram. Both extractable and insoluble organic matter in the carbonate rocks were interpreted to be indigenous to the Chuar sediments rather than having migrated in from younger sediments. Reynolds and others (1988, Abstract) suggested a subsiding lacustrine origin within the continent for the Chuar Group and noted that the dark mudstones contain as much as 5% TOC. Rock-Eval Tmax values generally range from 430 to 440 °C, placing particularly the upper part of the succession in the oil window. They further noted hydrogen index (HI) values of up to 190 mg HC/g TOC, and genetic potentials (S1 + S2) of up to 6 kg/ton (6000 ppm) demonstrating that the rocks still have potential for generating commercial accumulations of hydrocarbons. They further noted that if the Chuar Group is widely distributed or preserved in pre-Phanerozoic graben in northern Arizona or southern Utah, it could source either Proterozoic or overlying Paleozoic reservoirs.

Palacas and Reynolds (1989, Abstract) provided additional data. They stated over 1/2 of the Galeros and Kwagunt Formations consists of organic-rich, gray to black mudstone and siltstone. They characterized the 922 ft thick Walcott Member of the Kwagunt Formation as having good to excellent petroleum source rock potential. The lower half of the Walcott has an average TOC of 3% and ranges up to 7%. Hydrogen indices average 135 mg HC/g TOC and range up to 204 mg HC/g TOC. Genetic potentials (S1 + S2) average 6000 ppm and range to 16,000 ppm. Chloroform extractable organic material (EOM) ranges up to 4000 ppm (see Palacas, 1997, p. 132). Data for the upper half of the Walcott were incomplete but appeared to be as rich or richer than the lower half. The Walcott source rocks are within the oil window. The Awatubi Member of the Kwagunt is thermally mature and the Galeros Formation is thermally mature to overmature. Both rated as poor oil sources, but possible

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Figure 1. Index Map, Chuar Terrane, Eastern Grand Canyon, Arizona (from Ford and Breed, 1973, Fig. 1.)

Figure 2a. Sample Localities and Geology from Ford and Breed (1973, Fig. 1) and Ford (1990, Fig. 1). Nankoweap Canyon Area, Point Imperial 7.5' Quadrangle, Arizona.
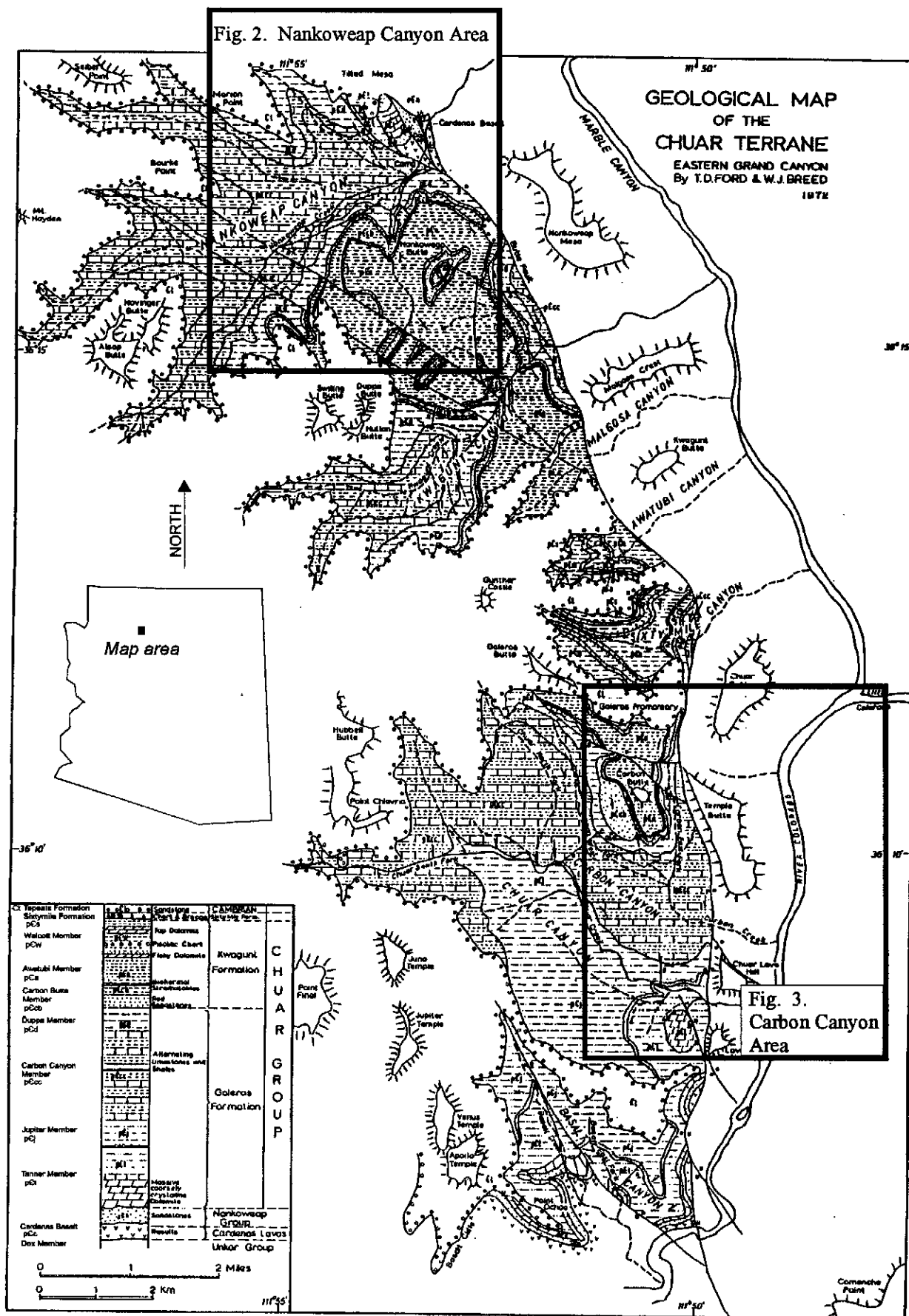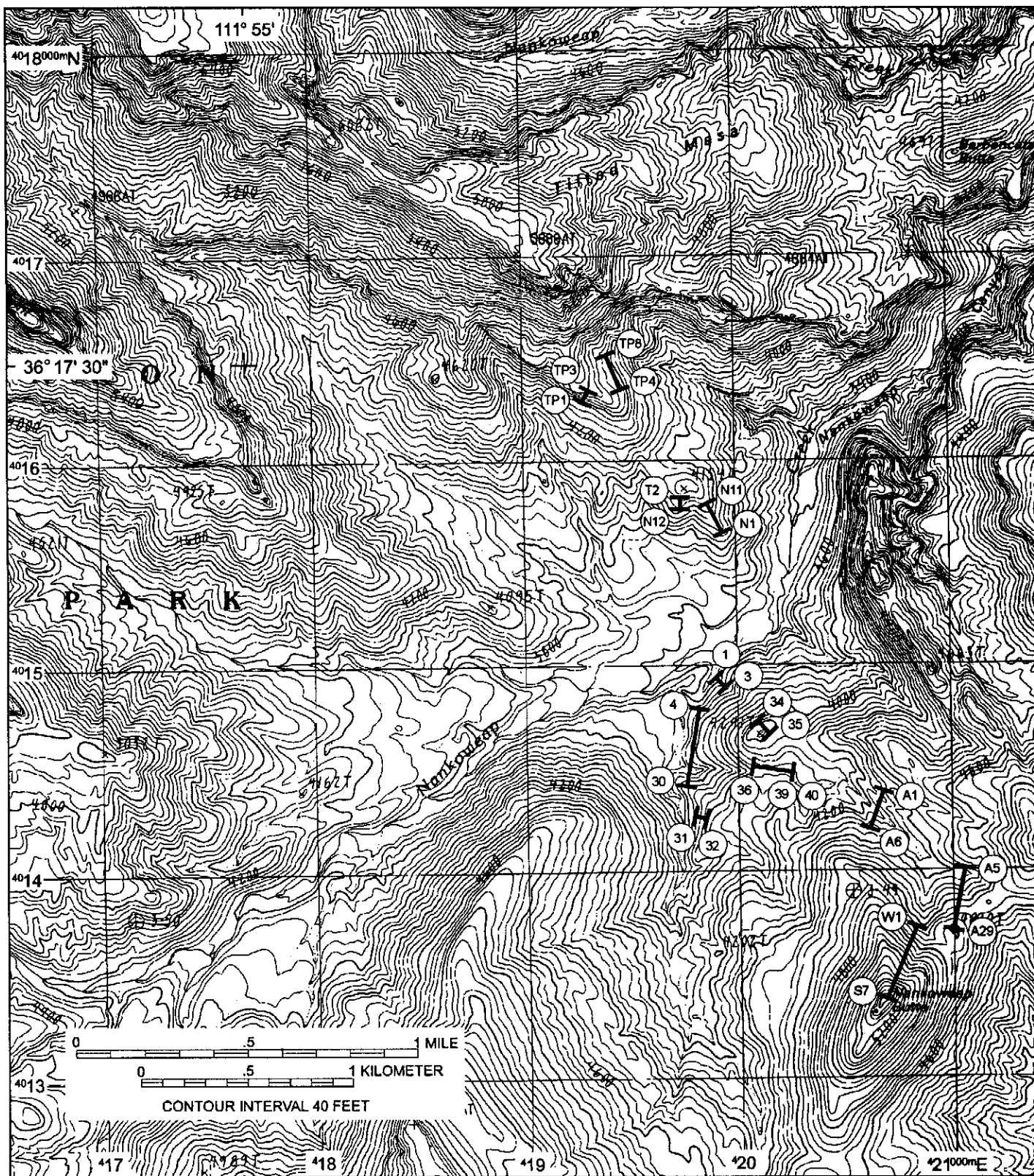
Figure 2b. Sample Localities and Topography, Nankoweap Canyon Area, Point Imperial 7.5' Quadrangle, Arizona.

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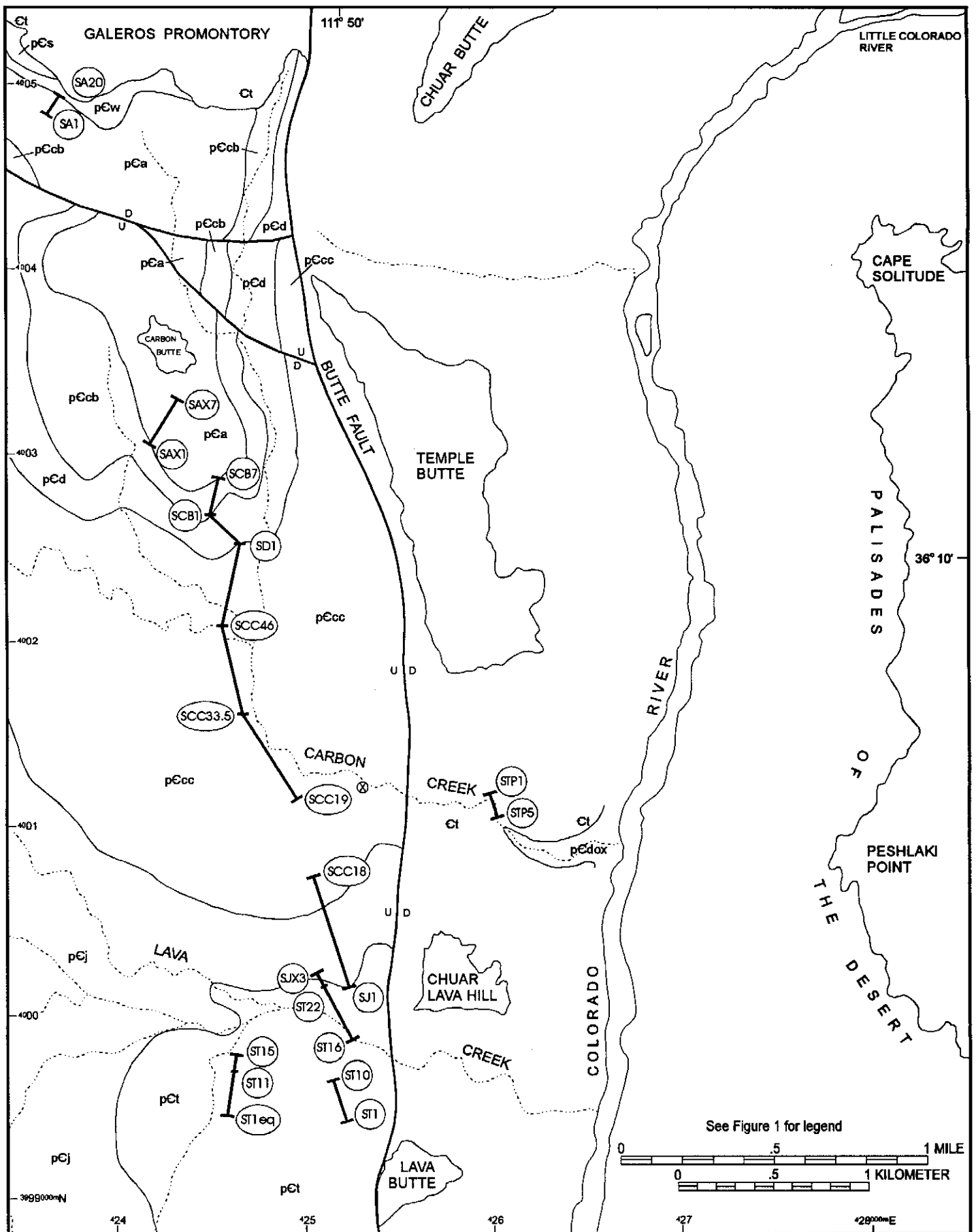
Figure 3a. Samples Localities and Geology from Ford and Breed (1973, Fig. 1), Carbon Canyon Area, Cape Solitude 7.5' Quadrangle, Arizona

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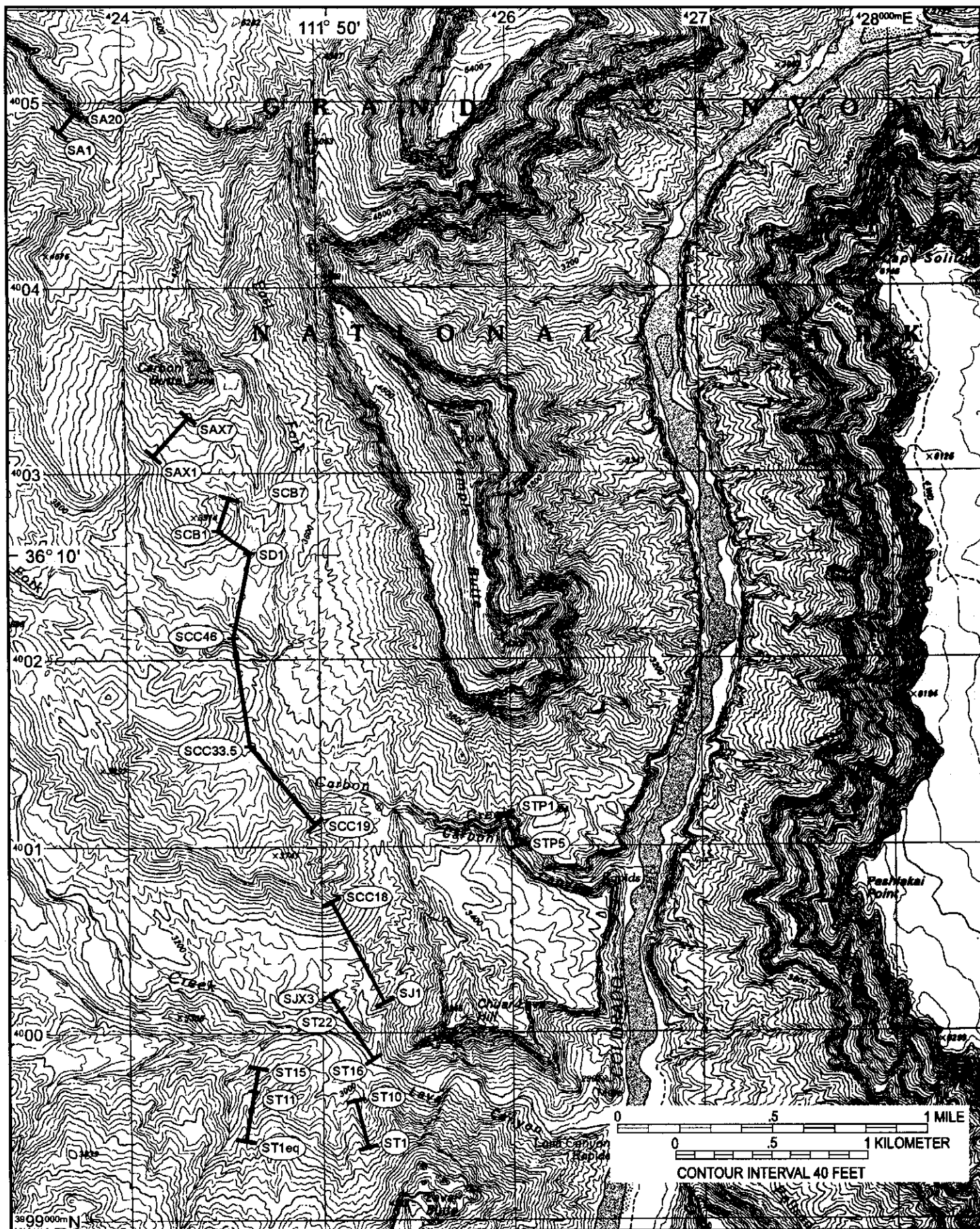
Figure 3b. Sample Localities and Topography, Carbon Canyon Area, Cape Solitude 7.5' Quadrangle, Arizona

TABLE 1. STRATIGRAPHY OF GRAND CANYON SUPERGROUP THROUGH BRIGHT ANGEL SHALE SHOWING MEASURED THICKNESSES OF THIS AND PREVIOUS STUDIES AND NUMBER OF SAMPLES THIS STUDY.

Age	Rock Unit	Ford, 1990; Ford & Breed 1973, p. 1244	Hintze, 1988, p. 199	Elston, 1989, p. 96	This Study Nankoweap area (# spls)	This Study Carbon Canyon area (# spls)	Approximate & est. ages (Ma) (Elston, 1989, p. 97)
€	Bright Angel Shale		200-500'				
€	Tapeats Sandstone		0-300'		225' (8)	48'+ (5)	~543*
LATE PROTEROZOIC — GRAND CANYON SUPERGROUP — CHUAR GROUP	Sixtymile Formation	120-200'	200'	194-210'+	185' (7)	abs, eroded (0)	~825
KWAGUNT FM	Walcott Member	838'	840'	922'	887' (36)	50' est (0)	
KWAGUNT FM	Awatubi Member	1128'	1230'	988'	855' (31)	771'+ (27)	
KWAGUNT FM	Carbon Butte Mbr	252'	250'	164'	157' (8)	247' (6)	850 est.
GALEROS FM	Duppa Member	570'	570'	341'	549' (10)	640' (16)	
GALEROS FM	Carbon Canyon Mbr	1546'	1550'	1148'	540'+ (21)	1060'(40)	
GALEROS FM	Jupiter Member	1516'	1520'	1424'		1545' (53)	
GALEROS FM	Tanner Member	640'	640'	512'	29'+ (2)	574' (22)	
MIDDLE PROTEROZOIC — UNKAR GROUP	Nankoweap Formation		300'+	371-820'	372' (10)		900 est.
UNKAR GROUP	Cardenas Basalt		700-1500'	735-1476'			950 est. / 1050 est. / ~1070
UNKAR GROUP	Dox Sandstone		3100'	3018'			~1110
UNKAR GROUP	Shinumo Quartzite		1000-1500'	1148'			~1130
UNKAR GROUP	Hakatai Shale		400-800'	410'			1200 est.
UNKAR GROUP	Bass Limestone		120-300'	262'			1250 est.

Section measured and samples collected this study: 3799' (133)   4935' (169)

Total: 8734' (302)

*Bowring and Erwin, 1998

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gas sources, with genetic potentials generally less than 1000 ppm. Several thin sequences in these units display good oil characteristics with EOM nearly 2000 ppm and genetic potentials nearly 7000 ppm.

Rauzi (1990) mapped the possible distribution of the Chuar Group in northern Arizona and southern Utah in an area bounded by the Kaibab Uplift on the west and the Monument Uplift on the east. His map included the Chuar outcrops in the Grand Canyon and noted its occurrence in the Tidewater No. 1 Kaibab Gulch well in Utah. He suggested (per D.P. Elston, personal communication, 1989) that the Chuar Group correlated with, and once may have been continuous with, the Red Pine Shale of the Uinta Mountain Group in north-central Utah. Rauzi suggested stratigraphic, structural, and unconformity traps involving both Chuar Group reservoirs and overlying Paleozoic reservoirs. He reported oil shows in the Cambrian Tapeats Sandstone in the Collins Cobb No. 1-X Navajo well and pointed out that some of the sandstones within the Chuar section in the Tidewater well had up to 6% porosity constituting potential reservoirs. He indicated that the Tapeats Sandstone and overlying impermeable Bright Angel Shale overlie the Chuar Group throughout his map area. Rauzi (1990) cited personal communications from Horodyski that strong hydrocarbon odors were evident 3 to 4 ft away from carbonate outcrops of the Walcott Member.

The Utah Geological Survey (1990) published a map showing the maximum areal extent of Chuar or Chuar equivalent rocks in the subsurface of Utah based on 7 wells penetrating these rocks and outcrops of Chuar equivalent rocks in the Uinta Mountains and near Salt Lake City. The Utah Survey further reported that oils from 2 Utah fields could not be correlated with any oil or known source rocks in Utah but were somewhat similar geochemically to Chuar Group rocks. The fields may have been sourced by Chuar rocks or other as yet unrecognized source rocks. Chidsey and others (1990, Abstract) noted that Chuar rocks were penetrated in the Tidewater No. 1 Kaibab Gulch well and that the Chuar Group may correlate with the Big Cottonwood Formation near Salt Lake City and the Red Pine Shale of the Uinta Mountain Group in outcrop. They also noted the potential for large petroleum field discoveries due to the sparsity of lower Paleozoic and Precambrian well penetrations in the area potentially underlain by Chuar equivalent rocks.

Paleontological correlation of the Chuar Group of the Grand Canyon and the Uinta Mountain Group of Utah has been supported by the work of Hoffman (1977) who reported Chuaria from the Uinta Mountain Group, and Vidal and Ford (1985) and Vidal (1986) who reported similar microbiotas from the 2 areas.

Cook (1991) provided the first detailed analysis of the source rock potential of the Walcott Member of the Chuar Group in the Grand Canyon outcrops. He measured, described, and analyzed samples from Nankoweap Butte and Sixtymile Canyon sections. Cook's measured sections of the Walcott are 793 ft thick at Nankoweap Butte and 763 ft thick at Sixtymile Canyon. In the Sixtymile Canyon section, the average TOC of 9 samples was 2.22%, with a range of .03 to 5.61%, and the average Tmax of 8 samples was 443 °C, with a range of 436 to 451 °C. In the Nankoweap Butte section, the average TOC of 57

samples was 2.43%, with a range of 0.33 to 8.87%, and the average Tmax of 53 samples was 436 °C, with a range of 381 to 479 °C. Cook provided additional detailed analyses and measured sections. He determined a Type II kerogen. Cook noted the common presence of ammonium illite in the Walcott which indicated Walcott source rocks had reached the oil window, generated oil, liberated ammonia, which was then incorporated into the illite interlayers. Cook postulated a lower intertidal to supratidal deposition on a shallow carbonate ramp within a marine embayment for the Walcott.

Palacas (1992; 1997) cited known examples of giant petroleum fields with Precambrian sources from diverse parts of the world including Oman, Eastern Siberia, and southwest China providing analogues for the Chuar Group as a significant petroleum source. He also evaluated the source rock potential of the Grand Canyon area of northern Arizona. More than half of the 5370 ft Chuar Group were reported to be organic-rich gray to black mudstone, shale, or siltstone. The lower half of the Walcott has an average TOC of 3% and ranges up to 8.0 to 10%. The Awatubi Member of the Kwagunt Formation and the Galeros Formation were reported to appear to be acceptable to good gas source rocks. Palacas provided a map of the possible distribution of Chuar Group or equivalent rocks in northern Arizona and Utah based on 8 wells and outcrops of Chuar equivalents in the Grand Canyon of Arizona, and the Uinta Mountains and near Salt Lake City in Utah.

Lillis and others (1995, Abstract) recorded oil shows and good reservoir characteristics in 2 southern Utah wildcat wells drilled in 1994: the Burnett No. 36-1 Federal and the BHP No. 28-1 Federal. The chemical composition of oil extracted from the Cambrian Tapeats Sandstone differed significantly from oils produced from Upper Valley Field (upper Paleozoic reservoirs) and the tar sands of southern and central Utah. The extracted oil appeared somewhat similar to Precambrian Chuar Group bitumen extracts from the Grand Canyon suggesting that this new oil type may be derived from Precambrian or Cambrian source rocks.

The Tar Sand Triangle of Utah is the largest deposit of heavy oil (tar) in the United States (Demaison, 1977). It was initially estimated to contain between 12.5 and 16 billion barrels original oil in place in the Permian White Rim Sandstone (Campbell and Ritzma, 1979, p. 4, Table 2). Corehole drilling in anticipation of production has reduced this estimate to 8 billion barrels original oil in place (Montgomery, 1983, p. 760). In addition, the Circle Cliffs Tar Sand deposits contain 1.3 billion barrels original oil in place in the Triassic Moenkopi Formation (Campbell and Ritzma, 1979, p. 4, Table 2). The source of these vast deposits has long been a mystery because Paleozoic shales in the area are redbeds with no suitably thick nor organically rich source-rock intervals to provide the volume of oil in the Tar Sand Triangle deposit. Sanford (1995) analyzed 10 potential source-rock units in the area and concluded that the most likely source is the Late Proterozoic Chuar Group in west-central Utah based on source-rock richness, thickness, and maturity and ground water flow history. No crude oil-source rock correlations were attempted.

The U.S. Geological Survey (1996) included this play as one of the hypothetical oil

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and gas plays (No. 2403) in the U.S. Onshore in their assessment of United States oil and gas resources. They noted that due to maturity increasing with depth and the Chuar being at greater depths in Utah than in Arizona, that the play is oil-prone in Arizona and gas prone in Utah. They assessed timing of petroleum generation and migration relative to trap formation as the big unknowns in the play. They noted that exploration for the Chuar (and Tapeats) is nearly non-existent. Oil and gas shows were reported in the Tidewater No. 1 Kaibab Federal well in both the Tapeats Sandstone (15 ft of oil) and in the Chuar Group. The mean size of individual accumulations was estimated at 18.2 million barrels of oil (MMBO) or 56.6 billion cubic feet of gas (BCFG). The upper 5% of the potential field size distribution was estimated at 500 MMBO or 400 BCFG. The mean play reserves were estimated at 35 MMBO equivalent if oil or 175 BCFG based on a mean of 1.8 oil accumulations or 1.8 gas accumulations and a play probability of success of 0.30. The upper 5% of the potential play size was estimated at 209.2 MMBO if oil or 722.7 BCFG if gas.

Uphoff (1997) provided a comprehensive overview of the Precambrian Chuar source rock play in southern Utah in which the Chuar Group is source, the Cambrian Tapeats Sandstone is reservoir, the Bright Angel Shale is seal, and the numerous Laramide anticlines not tested down to the Tapeats form the traps. He discussed Tapeats penetrations, hydrocarbon shows, and drill-stem tests relative to reservoir quality and gave a history of the BHP No. 28-1 Federal well. Uphoff calculated that the total generated hydrocarbon volume of a 150 sq mi portion of the Chuar fairway is between 2700 and 7300 MMBO and that, assuming a 25% entrapment rate, potential trapped oil in place is 700 to 1800 million barrels for this small portion of the Chuar fairway.

Reservoir and Source Rock Evaluation Guidelines

Reservoir Rock

Porosity. Productive guidelines for porosity used in this report are from Hilchie (1982, p. 1-7). Three percent porosity is the general productive minimum for carbonates. Seven percent porosity is the general productive minimum for gas in sandstones, and 8% porosity is the general productive minimum for oil in sandstones.

Permeability. The permeability classification used in this report is from Dresser Atlas (1982, p. 6). Permeability is rated as poor to fair if less than 15 millidarcies (md), moderate if from 15 to 50 md, good if from 50 to 250 md, very good if from 250 to 1000 md, and excellent if greater than 1000 md. This classification is supplemented with that of Sneider and others (1983, 1984) and Goolsby and others (1988) who classified rock Types I, II, and III based on rock permeabilities and productive capabilities. Type IA to IC have permeabilities greater than 1 md and are capable of oil and gas production without natural or

TABLE 2. SUMMARY OF RESERVOIR AND SOURCE ROCK DATA

ROCK UNIT	SOURCE ROCK POTENTIAL						RESERVOIR ROCK POTENTIAL					
	Organic richness (TOC %)			Organic maturity (Tmax)			Porosity % (helium)			Permeability (md)		
	#sp	range	ave	#sp	range	ave	#sp	range	ave	#sp	range	ave
Nankoweap Canyon Area												
Tapeats Fm	0	-	-	0	-	-	8	(92.7/8) 6.2-16.7	11.59	8	(304.2/8) 0.40-169	38.03
Sixtymile Fm	7	(0.34/7) 0.03-0.06	0.05	0	-	-	1	18.3	18.3	1	770	770
Walcott Mbr	32	(61.76/32) 0.07-8.29	1.93	26	(10806/26) 264-477	416	4	(9.8/4) 1.3-4.3	2.45	4	(0.64/4) 0.02-0.56	0.16
upper 165' Awatubi Mbr	7	(7.36/7) 0.26-1.64	1.05	5	(2048/5) 336-435	410	0	-	-	0	-	-
entire Awatubi Mbr	31	(13/31) 0.02-1.64	0.42	9	(3299/9) 249-435	367	0	-	-	0	-	-
Carbon Butte Mbr	2	(0.05/2) 0.02-0.03	0.03	0	-	-	6	(49.9/6) 2.3-13.1	8.32	6	(31.04/6) 0.06-19.3	5.17
Duppa Mbr	10	(0.65/10) 0.02-0.21	0.07	0	-	-	0	-	-	0	-	-
Carbon Canyon Mbr	19	(6.52/19) 0.01-3.20	0.34	2	(979/2) 482-497	490	1	6.0	6.0	1	0.14	0.14
basal dolomite Tanner Mbr	0	-	-	0	-	-	2	(10.1/2) 1.6-8.5	5.05	2	(0.81/2) 0.01-0.80	0.41
Nankoweap Fm	0	-	-	0	-	-	10	(63.9/10) 1.3-14.6	6.39	10	(50.73/10) 0.02-36.4	5.07
Carbon Canyon Area												
Tapeats Fm	0	-	-	0	-	-	5	(40.4/5) 5.0-11.6	8.08	5	(5.93/5) 0.03-3.84	1.19
Walcott Mbr	0	-	-	0	-	-	0	-	-	0	-	-
upper 390' Awatubi Mbr	13	(15.32/13) 0.05-3.77	1.18	11	(4534/11) 324-438	412	0	-	-	0	-	-
entire Awatubi Mbr	27	(16.13/27) 0.02-3.77	0.60	11	(4534/11) 324-438	412	1	0.3	0.3	1	0.02	0.02
Carbon Butte Mbr	0	-	-	0	-	-	6	(44.2/6) 0.3-12.4	7.37	6	(15.44/6) 0.02-13.4	2.57
Duppa Mbr	16	(0.84/16) 0.01-0.23	0.05	0	-	-	0	-	-	0	-	-
Carbon Canyon Mbr	38	(7.46/38) 0.01-2.64	0.20	2	(913/2) 449-464	457	1	12.5	12.5	1	0.10	0.10
Jupiter Mbr	53	(7.45/53) 0.02-0.86	0.14	1	276	276	2	(6.6/2) 2.7-3.9	3.3	2	(0.12/2) 0.04-0.08	0.06
Tanner Mbr	22	(7.37/22) 0.02-1.41	0.34	2	(791/2) 276-515	396	0	-	-	0	-	-

TABLE 3. RESERVOIR AND SOURCE ROCK POTENTIAL BY FORMATION / MEMBER

(NCA = Nankoweap Canyon Area - Plate 2; CCA = Carbon Canyon Area - Plate 1)

Formation or Member	RESERVOIR POTENTIAL		SOURCE ROCK POTENTIAL	
	Porosity	Permeability (md)	Organic Richness (TOC)	Maturity
Tapeats Formation	NCA: 207' ≥ 7% (gas res pot) 202' ≥ 8% (oil res pot) CCA: measured only basal 47.5' 32' ≥ 7% (gas reservoir pot) 25' ≥ 8% (oil res potential)	NCA: 205' ≥ 0.5 (gas res pot) 121' ≥ 15 (moderate perm) 42' ≥ 50 (good perm) CCA: measured only basal 47.5' 19' ≥ 0.5 (gas res pot)	Not a source rock	Not a source rock
Sixtymile Formation	NCA: 1 spl & uppermost 30' (?) had 18.3% (gas/oil res pot)	NCA: 1 spl & uppermost 30' (?) had 770 (gas/oil res pot)	NCA: Entirely poor source rock (7 samples)	NCA: Maturity not measured projected from below to be immature
Walcott Member	NCA: Upper 2 dolomites: 4' section ≥ 3% (prod min (for carbonates)	NCA: Upper 2 dolomites: 2' section ≥ 0.5 (gas res pot) 4 samples = poor to fair	NCA: 773' section fair or better 744' section good or better 362' section very good or better 127' section excellent	NCA: 425°C (immature) at top, 445°C (early oil/peak oil boundary) at base. Upper 434' immature; lower 453' early oil.
Awatubi Member	CCA: 1 spl basal stromatolitic dol 0.3% (non-productive)	CCA: 0.02 (poor to fair) = Type III, non productive	NCA: 221' section fair or better 77' good. CCA: 267' section fair or better 127' good or better, 50' very good	NCA: Peak oil at top to late oil at base CCA: Immature at top to early oil at base
Carbon Butte Member	NCA: 100' ≥ 7%; 95' ≥ 8% CCA: 116' ≥ 7%; 89' ≥ 8%	NCA: 44 or 77' ≥ 0.5 (gas res pot) 4' moderate, rest poor to fair CCA: 144' ≥ 0.5 (gas res pot) All poor to fair	Poor source rocks	NCA: Tmax grad: Late oil window CCA: Tmax grad: Early oil to peak oil window
Duppa Member	No reservoir rock recognized	No reservoir rock recognized	Entirely poor source rock	NCA: Late oil to condensate/wet gas CCA: Peak oil to late oil window
Carbon Canyon Member	2 spls from 2 stromatolitic ls/dol units with 6-12.5% (potentially productive), (20' & 10-15' thick each)	Same 2 samples with 0' of ≤ 0.5 (both samples poor to fair perm)	NCA: Spld only upper 540' of 1060' 63' fair or better; 42' good or better; 25' very good CCA: 86' fair or better; 36' good or better; 8' very good	NCA: Condensate/wet gas to dry gas window CCA: Late oil to condensate/wet gas window
Jupiter Member	CCA: 1 spl & 6' of basal stromatolitic ls w/ ≥ 3% (potentially productive)	CCA: 0' with ≥ 0.5 (Type I) All basal stromatolitic ls is poor to fair perm.	CCA: 3 spls & 35' fair	CCA: upper 1161' of section in condensate/wet gas window; lower 384' in dry gas window Tmax=478°C at top; 507°C at base
Tanner Member	1 spl & 19' basal dol ≥ 3% (pot prod); only 29' out of 64' of basal dol analyzed	3' ≥ 0.5 (Type I); basal dol = poor to fair perm; only 29' out of 64' of basal dol analyzed	CCA: 71' of section fair or better; 14' of section good	CCA: Dry gas window; Tmax grad = 507°C at top; 516°C at base
Nankoweap Formation	NCA: 3 spls & 130' of section ≥ 7% (potentially productive)	NCA: 98' of section ≥ 0.5 (Type I); 1 spl & 17' of section = mod perm	Not a source rock	Not a source rock

artificial fracturing if thick enough. Type ID, with a permeability range of 0.5 to 1.0 md, is capable of gas production without natural or artificial fracturing if thick enough. Type II, with a permeability range of 0.07 to 0.5 md, is capable of gas production if interlayered with Type I rock or has natural, open fractures or is artificially fractured and is thick enough. Type III rock, with a permeability less than 0.07 md, is too tight to produce at commercial rates. Permeability of 0.5 md, which is the boundary between Type I and Type II rock, is taken as the cutoff for estimating potentially productive permeability in this study.

Source Rock

Organic Richness. The organic richness rating used in this report is that of Peters and Cassa (1994, p. 95), and is rated as poor if 0 to 0.5 wt % TOC, fair if 0.5 to 1.0 wt % TOC, good if 1.0 to 2.0 wt % TOC, very good if 2.0 to 4.0 wt % TOC, and excellent if above 4.0 wt % TOC.

Source Maturity and Principal Stage of Petroleum Generation. The source maturity and principal stage of petroleum generation classification used in this report is a combination of that of Peters and Cassa (1994, p. 94-96), Hood and others (1975, p. 993), and Vassoyevich and others (1970). Pyrolysis Tmax values below 435 °C are considered immature and will only generate diagenetic or biogenic methane. The early oil window is from Tmax of 435 to 445 °C. The peak oil window is from 445 to 450 °C. The late oil window is from 450 to 470 °C. The condensate and wet gas window is from 470 to 500 °C. The dry gas window includes Tmax values above 500 °C where only metagenetic methane will be generated.

Previous Status of Grand Canyon Chuar Source Rock Potential

Walcott Member of Kwagunt Formation

Thickness estimates of the Walcott Member of the Kwagunt Formation range from 763 ft (Sixtymile Canyon Section, Cook, 1991) to 922 ft (Elston, 1989, p. 96). Strong hydrocarbon odor is evident 3 to 4 ft from the outcrop of carbonate units of this member (Rauzi, 1990).

Cook (1991) provided excellent stratigraphicically detailed geochemical data for this member. In the 793 ft Nankoweap Butte section, the average organic richness of 57 samples was 2.43% TOC (very good) with a range of 0.33% (poor) to 8.87% (excellent). The average maturity (Tmax) of 53 samples was 436 °C (early oil window) with a range of 381 °C (immature) to 479 °C (condensate and wet gas window). In the 763 ft Sixtymile Canyon section, the average organic richness of 9 samples was 2.22% TOC (very good) with a range

of 0.03% (poor) to 5.61% (excellent). The average maturity (Tmax) of 8 samples was 443 °C (early oil) with a range of 436 °C (early oil) to 451 °C (late oil). Cook determined the kerogen to be Type II and noted that the common presence of 25% ammonium illite in clays indicated that Walcott source rocks had reached the oil window and generated oil.

Palacas and Reynolds (1989) and Palacas (1992, 1997) reported that the lower half of the 922 ft thick Walcott Member had an average TOC of 3% and ranged up to 7%. Hydrogen indices averaged 135 mg HC/g TOC and ranged up to 204 mg HC/g TOC. Genetic potentials (S1 + S2) averaged 6000 ppm and ranged up to 16,000 ppm. Chloroform EOM ranged up to 4000 ppm. Palacas and Reynolds (1990?) reported full analytical details on a single Walcott black shale sample 10 ft above the base of the member in the Nankoweap Canyon section with a vitrinite-like reflectance of 0.76% (peak oil window) and a Tmax of 441 °C (early oil window).

Summons and others (1988) identified Type I-II kerogen from the Walcott in the mature (oil window) region of the Van Krevelen diagram. Both extractable and insoluble organic matter were interpreted to be indigenous to the Chuar sediments, rather than having migrated from younger sediments.

Awatubi Member of Kwagunt Formation

The Awatubi Member of the Kwagunt Formation has a measured thickness of 1128 ft (Ford and Breed, 1973). An abstract by Palacas and Reynolds (1989) and reports by Palacas (1992, 1997) indicate the member is thermally mature (oil window). Based on genetic potentials (S1 + S2) generally less than 1000 ppm, the Awatubi Member is a poor oil source but a possible or an acceptable to good gas source. Several thin beds display good oil characteristics with EOM of nearly 2000 ppm and genetic potentials of nearly 7000 ppm. Stratigraphically detailed sample analyses of the Awatubi Member have not been available.

Galeros Formation

Ford and Breed (1973) measured the thickness of the Galeros Formation as 4272 ft. An abstract by Palacas and Reynolds (1989) and reports by Palacas (1992, 1997) assess the maturity of the Galeros Formation as thermally mature to overmature. The Galeros Formation is also a poor oil source but a possible or an acceptable to good gas source, based on genetic potentials generally less than 1000 ppm. Several thin beds display good oil characteristics with EOM of nearly 2000 ppm and genetic potentials of nearly 7000 ppm. Stratigraphically detailed sample analyses of the Galeros Formation have not been available.

Summary of Previous Source and Reservoir Rock Information

The work summarized above implied the possibility that the Chuar Group could contain petroleum source rocks in excess of 1 mile (6322 ft) in thickness. The 763 to 922 ft thick Walcott Member is a potential oil source rock, documented in excellent stratigraphic detail. Its average organic richness is very good (2.22 to 2.43% TOC) and the average maturity is in the early oil window (average Tmax is 436 to 443 °C). The kerogen is Type I to II. The extractable and insoluble organic matter is indigenous to the formation, and not migrated from other formations.

While no stratigraphically detailed sample analyses were available, generalized reports suggested that both the Awatubi Member of the Kwagunt Formation and the Galeros Formation were possible or acceptable to good gas source rocks. The Awatubi Member is in the oil window (thermally mature) and the Galeros Formation is in the oil to dry gas window (thermally mature to overmature). Both the Awatubi and the Galeros were reported to have thin beds with good oil source rock potential.

Hydrocarbons generated from source rocks generally migrate vertically until a carrier bed is encountered which allows lateral migration. If the Galeros Formation and the Awatubi and Walcott Members of the Kwagunt Formation are all source rocks, overlying and interbedded potential reservoirs include the 94 ft thick basal sandstone unit of the Carbon Butte Member of the Kwagunt Formation (Ford and Breed, 1973, p. 1250) and the blanket sandstones of the Tapeats Formation, which range in thickness from 0 to 300 ft (Uphoff, 1997, p. 4). In addition, the carbonate beds of the Tanner, Jupiter, Carbon Canyon, Awatubi, and Walcott Members of the Chuar Group might all be potential reservoirs.

Sears (1990, especially Figures 1, 3, 6, and 8) suggests that the Grand Canyon Supergroup is preserved in half graben related to Late Proterozoic continental rifting and that the rifting is extensive in western North America from California to the Yukon. This suggests that the 300 to 370 ft thick Nankoweap Formation is a potential reservoir on the upthrown side of the half graben where it may be in fault-contact with the Chuar Group source rocks on the downthrown side of the fault.

Virtually no porosity and permeability data has been published on any of these potential reservoir rocks. Two goals of the present study were to sample and analyze (1) the reservoir characteristics of these potential reservoir rocks and (2) the entire Chuar Group for source rock potential at approximately 30 ft stratigraphic increments.

Methods

Field

In October 1996, two stratigraphic sections of the Late Proterozoic Chuar Group, located in the Nankoweap Canyon (Figure 2) and Carbon Canyon (Figure 3) areas of the eastern Grand Canyon National Park, Arizona (Figure 1), were measured, described, and sampled. The mapping used in this report was that of Ford and Breed (1973), as slightly modified in the Nankoweap Canyon area by Ford (1990, p. 50, Figure 1). These 2 maps were supplemented with that of Huntoon and others (1996) especially with respect to some of the structural features mapped and the Tapeats mapping.

The field party, the 6 authors of the current report, was divided into 2 groups of 3 each in order to measure the maximum footage of section in the time available. Stratigraphic sections were measured with a Jacob's staff and Abney level or a brunton compass mounted on an Abney level. Samples were collected at approximately 30 ft stratigraphic intervals. Sampling was accomplished using rock hammers to dig a 1 ft long by 1 ft deep pit to obtain relatively unweathered samples approximately 3 inches by 3 inches in size and collected in waterproof sample bags. The pits were immediately refilled. Localities and sampling traverses were spotted on 7.5' topographic quadrangle maps. In the Nankoweap Canyon area, 3799 ft of section were measured and described and 133 samples were collected. In the Carbon Canyon area, 4935 ft of section were measured and described and 169 samples were collected. A total of 8734 ft of section was measured and 302 samples were collected.

The outcrops were reached by rafting down the Colorado River from Lees Ferry, Arizona, to the junction of each canyon area (Nankoweap and Carbon Canyons), and then backpacking to the upper reaches of each canyon and camping and working for 3 days in each area (6 total collecting and section measuring days). Samples were backpacked to camp and back down each canyon to the Colorado River, and rafted out to the disembarkation point at Diamond Creek, on the Hualapi Indian Reservation. Outdoor Adventure River Specialists, Inc. (O.A.R.S., Inc.) of Angels Camp, California, provided guide service, logistical support, and rafting transportation with 3 inflatable hand-rowed rafts.

Analysis

About 1/2 of each sample was analyzed for petroleum reservoir and/or petroleum source rock potential. A total of 47 samples were analyzed for reservoir characteristics by Core Laboratories, Inc. of Midland, Texas. Reservoir sample analysis included permeability, porosity, and grain density. A total of 258 samples were analyzed geochemically for source rock potential by DGSI of The Woodlands, Texas, as a

subcontractor of Baseline Resolution, Inc. of Plano, Texas. All 258 of these samples were analyzed for TOC as a measure of organic richness, and the 65 samples with TOC yields of 0.5 wt % or greater were run for Rock-Eval pyrolysis, which included Tmax as a measure of thermal maturity. Based on these results 31 samples were chosen for organic petrographic study. Organic petrography was conducted on whole rock plugs in reflected light, plus macerated kerogen concentrates in reflected and transmitted light. Organic petrography was conducted in this fashion because the formations analyzed are exclusively Precambrian, and as no vitrinite existed during this time period, it was important to ascertain (as much as possible) the nature of the organic material that was measured. The Rock-Eval pyrolysis measured S1 (mg/g), S2 (mg/g), S3 (mg/g), Tmax (°C), S1/TOC, HI, OI, S2/S3, and PI. Thirty samples were analyzed for compositional data both by weight and percent including saturated, aromatic, resin (nitrogen, sulfur, and oxygen compounds), and asphaltene fractions (Table 5 and Figure 7). These same 30 samples were also analyzed for stable carbon isotope ratios, including del C13 Saturate and del C13 Aromatic to estimate marine vs. nonmarine origin (Table 6 and Figure 8).

Four samples were analyzed for both reservoir and source rock potential. One sample was missing.

The remaining 1/2 of each sample has been deposited with the Arizona Geological Survey to establish a collection available for future study of these outcrops which are remote and difficult and expensive to access, requiring either backpacking and/or rafting or helicopter transportation in and out.

Stratigraphy

A comparison of member and formational thicknesses as measured in the present study, and as compared to previous authors, is shown in Table 1. Stratigraphic details are included on the composite stratigraphic cross section (Plates 1 and 2) and in the field notes (Appendix 2). The Walcott Member thickness as measured in this report in the Nankoweap Canyon area is 887 ft. This is intermediate between thicknesses of 793 ft (Cook, 1991, at Nankoweap Butte), 763 ft (Cook, 1991, at Sixtymile Canyon), 838 ft (Ford and Breed, 1973; and Ford, 1990), and 840 ft (Hintze, 1988) on the one hand; and 922 ft measured by Elston (1989) on the other.

We measured the Awatubi Member to be 855 ft thick in the Nankoweap Canyon area, which is somewhat less than the other authors listed in Table 1. In Carbon Canyon, 2 incomplete sections of the Awatubi were measured: a basal section with the top covered by the Carbon Butte landslide mass, and a capping section with no base established. The basal section, designated SAX, consisted of 191 ft of section measured upward from the Awatubi Member's basal stromatolite bed. The top of the SAX section was not established because it was covered. In the large canyon south of the Galeros Promontory (Figure 1), 580 ft (480 ft

measured and 100 ft estimated) of Awatubi, designated the SA section, was described below the base of the Walcott flaky dolomite. It was estimated that as much as 1000 to 1500 ft of unmeasured Awatubi might lie below the SA section. The Carbon Butte Member was not located in the canyon below the Galeros Promontory to establish the base of the Awatubi there because of time limitations. Thus in the general Carbon Canyon area, 771 ft (191 + 580 ft) of section was described in the 2 partial sections. A minimum gap between the basal SAX section and the capping SA section is estimated at 84 ft (855 - 771 ft) compared to the Nankoweap Canyon area, or 359 ft (1130 - 771 ft) compared to Ford and Breed (1973). Maximum Awatubi thickness in the Carbon Canyon area could be as much as 2080 ft (1500 + 580 ft), though this is highly suspect since the Carbon Butte Member was not found to establish the base of the Awatubi in the SA section.

The thickness of the Carbon Butte Member was 247 ft in the Carbon Canyon area but only 157 ft in the Nankoweap Canyon area.

In the Carbon Canyon area, we measured the Carbon Canyon Member thickness as 1060 ft, which is somewhat thinner than previous authors in Table 1, whose thicknesses ranged from 1148 to 1550 ft.

Thicknesses of other units measured in the current report are fairly close to those reported by previous authors.

Source Rock Potential and Reservoir Rock Potential by Stratigraphic Unit

Source rock and reservoir rock interpretations for each formation or member are summarized in Table 3. Statements in this section and in Table 3 concerning thicknesses of potential reservoir and source rock in a given formation or member are accurate only to within the approximate 30 ft sampling interval used in this study. Thicknesses are estimated by measuring the vertical thickness at the intersection of a vertical property ranking cutoff line (e.g. the 7% porosity line) and of the point to point data curves plotted on Plates 1 and 2. Since these are outcrop samples, reservoir properties may have been altered by exposure, requiring caution in applying results directly to the subsurface, however, several units do appear to have at least potential reservoir properties.

Nankoweap Formation

The Nankoweap Formation was only sampled in the Nankoweap Canyon area. Porosity of 10 samples ranged from 1.3 to 14.6% and averaged 6.39%. Based on the point to point curve plotted on Plate 2, three samples, and possibly 130 ft of section, may have greater than 7% porosity, the general minimum for gas production in sandstone (Hilchie, 1982, p. 1-7). Permeability of 10 samples ranged from 0.02 to 36.4 md and averaged 5.07

md (poor to fair). Based on Plate 2, about 98 ft of section had greater than 0.5 md permeability constituting Type I rock. One sample, and possibly 17 ft of section, may have moderate permeability. The rest of the section has poor to fair permeability. Thus between 98 and 130 ft of the Nankoweap Formation has reservoir potential.

This formation appeared to have no source rock potential and was, therefore, not analyzed for source rock characteristics.

Tanner Member of Galeros Formation

The basal dolomite of the Tanner Member was analyzed for reservoir potential in the Nankoweap Canyon area. Porosity of 2 samples was 1.6 to 8.5%, averaging 5.05%. Based on Plate 2, one sample, and possibly 19 ft of section, had greater than 3% porosity, the general productive minimum for carbonates (Hilchie, 1982, p. 1-7). Permeability of 2 samples ranged from 0.01 to 0.80 md, averaged 0.41 md, and was entirely in the poor to fair range. About 3 ft of section had permeability greater than 0.5 md (Type I rock). Only 29 of the 64 ft of total Tanner dolomite measured by Ford and Breed (1973) were sampled.

In the Carbon Canyon area, 510 ft of Tanner Member shales, which overlie the Tanner Member Dolomite, were sampled for source rock analysis. TOC's of 22 samples ranged from 0.02 (poor) to 1.41% (good), and averaged 0.34% (poor). Based on Plate 1, about 14 ft of Tanner may be good source rock (1 to 2% TOC). An additional 57 ft of Tanner may be fair source rock (0.5 to 1% TOC), giving a possible total of 71 ft of section which is fair or better source rock. Only 1 Tanner sample (ST4) had a Tmax analysis, which was 515 °C (dry gas window). Based on the eyeball best fit Tmax gradient line for the Carbon Canyon section (Plate 1), the entire Tanner Member is in the dry gas window, ranging from about 507 °C at the top to about 516 °C at the base. It should be noted, however, that the slope of this gradient is largely based on this single data point. In the Nankoweap Canyon area section, no data is available for the Tanner section, but based on extrapolating data from the overlying units downward, the Tanner would be in the dry gas window or greater in maturity.

Jupiter Member of Galeros Formation

The Jupiter Member was only sampled in the Carbon Canyon area, where it is 1545 ft thick. The basal 35 ft is a stromatolitic limestone which was sampled for reservoir properties, and the overlying 1510 ft is shale, which was sampled for source rock properties. Two samples from the basal stromatolitic limestone had porosities ranging from 2.7 to 3.9% and averaged 3.3%. One sample, and about 6 ft of section, had porosity greater than the 3% general productive minimum for carbonates. Permeabilities in these 2 samples ranged from

0.04 to 0.08 md, and averaged 0.06 md. All these permeability values are in the poor to fair range. Neither sample had permeabilities greater than 0.5 md of the Type I rock category.

Fifty-three samples of the upper 1510 ft thick Jupiter shale unit were sampled for source rock properties. TOC's ranged from 0.02 (poor) to 0.86% (fair), and averaged 0.14% (poor). Based on Plate 1, three samples, and about 35 ft of section, are fair source rocks (0.5 to 1.0% TOC). Based on the eyeball best Tmax gradient for the Carbon Canyon area section, the upper 1161 ft of the Jupiter is in the condensate and wet gas window, and the basal 384 ft of the Jupiter is in the dry gas window. The member has a Tmax gradient ranging from 478 °C at the top to 507 °C at the base.

Carbon Canyon Member of Galeros Formation

Two samples of Carbon Canyon Member carbonates were analyzed for reservoir potential. In the Carbon Canyon area section, a vuggy limestone or dolomite from 116 ft above the base of the section had 12.5% porosity (potentially productive for carbonates) and 0.10 md of permeability (poor to fair). In the Nankoweap Canyon area section, a stromatolitic limestone near the middle of the formation had 6% porosity (potentially productive for carbonates) and 0.14 md of permeability (poor to fair). Neither sample had greater than 0.5 md of permeability (Type I rock).

In the Carbon Canyon area section, 3 samples, and about 86 of the 1060 ft thick Carbon Canyon Member, had fair or better organic richness (0.5% TOC or greater). Two samples, and about 36 of this 86 ft, rated as good or better in TOC content (1% TOC or greater), and 1 sample, and about 8 ft of this, rated as very good in TOC content (2 - 4% TOC).

In the Nankoweap Canyon area section, only the upper 540 ft (of the 1060 ft seen in the Carbon Canyon area section) of the member were sampled and measured. In this section, 3 samples, and possibly 63 ft of section, had fair or greater organic richness. One sample, and about 42 of this 63 ft, had good or better richness; and 1 sample, and about 25 of this 42 ft, rated as very good in TOC content.

In the Carbon Canyon section, measured maturity on 2 samples ranged from 449 to 464 °C. The Tmax gradient ranges from 459 °C at the top to 477 °C at the base. The upper 591 ft of the member are in the late oil window and the lower 469 ft of the member are in the condensate and wet gas window.

In the Nankoweap Canyon area section, 2 samples had measured Tmax values of 497 and 482 °C. Sample CC1, with the 482 °C Tmax value, was a random sample from the lower part of the measured portion of the Carbon Canyon Member and its exact stratigraphic position within this member is uncertain. Its organic richness of 2.67% TOC, lithology, and rough stratigraphic position appear to equate to sample 4 (3.20% TOC). The Tmax gradient in the member in the Nankoweap Canyon area section ranged from 480 °C at the top to about

504 °C at the projected base. The upper 871 ft of the member lie in the condensate and wet gas window. The lower 189 ft, though not sampled or measured in the Nankoweap Canyon area, are projected to lie in the dry gas window.

Duppa Member of Galeros Formation

No potential reservoir beds were recognized or analyzed in the Duppa Member. The Duppa Member consisted largely of red, green, and grey shales and siltstones and appeared in the field to be low in organic content. Laboratory analysis has borne this out. In the Carbon Canyon area, 16 Duppa samples have TOC's ranging from 0.01 (poor) to 0.23% (poor), averaging 0.05% (poor). In the Nankoweap Canyon area section, 10 Duppa samples have TOC's ranging from 0.02 (poor) to 0.21% (poor), averaging 0.07% (poor).

No Tmax values were measured in either section due to the low TOC's. In the Carbon Canyon area section, the projected Tmax gradient line was 447 °C at the top of the member and 459 °C at the base of the member. The upper 131 ft of the member lie in the peak oil window and the lower 509 ft of the member lie in the late oil window. In the Nankoweap Canyon area section, the projected Tmax gradient line is 467.5 °C at the top and 480 °C at the base of the member. The upper 90 ft of the member lie in the late oil window, while the lower 459 ft of the member are in the condensate and wet gas window.

Carbon Butte Member of Kwagunt Formation

The Carbon Butte Member appears to be a potential reservoir unit. In the Carbon Canyon area section, porosity of 6 samples ranges from 0.3 to 12.4% and averages 7.37%. Two samples, and possibly 116 ft of section, have porosities of 7% or greater, the general minimum for gas production in sandstones. Two samples, and about 89 ft of section, had porosities of 8% or greater, the general minimum for oil production in sandstones. Permeability in the entire section, based on 6 samples, is in the poor to fair range. Permeabilities range from 0.02 to 13.4 md, and average 2.57 md. About 144 ft of section have a permeability greater than 0.5 md constituting Type I rock.

In the Nankoweap Canyon area section, porosity of 6 samples ranges from 2.3 to 13.1% and averages 8.32%. Four samples, and perhaps 100 ft of section, had porosities greater than 7%, the general productive minimum for gas in sandstone; and 3 samples, and perhaps 95 ft of section, had porosities greater than 8%, the general productive minimum for oil in sandstones. Permeabilities of 6 samples range from 0.06 to 19.3 md, and average 5.17 md. One sample, and perhaps 4 ft of section, had moderate permeability. The permeability of the remaining samples is in the poor to fair range. Either 44 or 77 ft of section have a permeability greater than 0.5 md constituting Type I rock.

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In the Nankoweap Canyon area, 2 samples were analyzed for source rock potential. They had a TOC content of 0.02 to 0.03%, and were both poor source rocks.

No maturity data were measured for this member in either area due to the poor TOC values. In the Carbon Canyon area, the projected Tmax gradient line is 443 °C (early oil window) at the top of the member and 447.5 °C (peak oil window) at the base. In the Nankoweap Canyon area, the projected Tmax gradient line lies entirely within the late oil window, being 464 °C at the top of the member and 467.5 °C at the base.

Awatubi Member of Kwagunt Formation

Only 1 sample of the Awatubi Member was analyzed for reservoir potential. This was Sample SAX1, from the Awatubi basal stromatolitic dolomite, 3 ft above the base of the member in the Carbon Canyon area. Porosity was 0.3% (non-productive) and permeability was 0.02 md (poor to fair). This permeability is less than that of 0.5 md, the lower limit of Type I rock.

In both the Carbon Canyon and Nankoweap Canyon areas, the upper portion of the Awatubi Member exhibits a dramatic increase in organic richness. In the Carbon Canyon area section, this occurs in the upper 390 ft. Here, all but 2 of the 13 samples in this interval have TOC's of fair or better (0.5% TOC or greater). Similarly, in the upper 165 ft of the Nankoweap Canyon area section, 6 of the 7 samples from this interval have TOC's of fair or better. We suggest that it is this upper portion of the Awatubi and the overlying Walcott Member which constitute the significant source rock potential of the Chuar Group.

In the Nankoweap Canyon area section, 31 samples from the 855 ft thick Awatubi Member have a TOC content ranging from 0.02 (poor) to 1.64% (good), and averaging 0.42% (poor). By comparison, the 7 samples from the upper 165 ft of the Awatubi have TOC's ranging from 0.26 (poor) to 1.64% (good), and averaging 1.05% (good). About 221 ft of section rate as fair or better source rock (0.5% TOC or greater), and about 77 ft of this 221 ft rate as good source rock (1.0 to 2.0% TOC). All of the good source rock and all but 72 ft of the fair or better source rock occur in the upper 165 ft of the member.

Nine Tmax values from the entire 855 ft Awatubi section range from 249 °C (immature) to 435 °C (immature/early oil boundary), and average 367 °C (immature). Five Tmax values from the upper 165 ft of the Awatubi range from 336 °C (immature) to 435 °C (immature/early oil boundary), and average 410 °C (immature). The Tmax gradient line ranges from 445.5 °C (early oil) at the top of the member, to 458.5 °C (late oil) 165 ft below the top (base of rich source rock), to 467.5 °C (late oil) at the base.

In the Carbon Canyon area section, 27 samples from the 771'+ of measured Awatubi Member have a TOC content ranging from 0.02 (poor) to 3.77% (very good), and averaging 0.60% (fair). Thirteen samples from the upper 390 ft of the Awatubi have a TOC content ranging from 0.05 (poor) to 3.77% (very good), and averaging 1.18% (good). About 267 of

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the 390 ft rate as fair or better source rock (0.5% TOC or greater) and about 127 of the 267 ft rate as good or better source rock (1.0 to 2.0% TOC). About 50 of the 127 ft rank as very good source rock (2.0 to 4.0% TOC). All of the very good and good source rock occur in the upper 390 ft of the section, and all but 8 ft of the fair source rock occurs in the upper 390 ft.

Eleven Tmax values from the entire Awatubi section range from 324 °C (immature) to 438 °C (early oil), and average 412 °C (immature). These 11 values all were measured in the upper 390 ft of the section (due to the high TOC values). The Tmax gradient line ranges from 427.5 °C (immature) at the top of the member, to 434 °C (immature) 390 ft below the top (base of rich source rock) to 443 °C (early oil) at the base of the member.

Walcott Member of Kwagunt Formation

In the Carbon Canyon area, the Walcott Member was observed to be about 50 ft thick where mapped by Ford and Breed (1973) unconformably below the Tapeats, but it was not sampled due to the steep cliff slope of the outcrop. The Walcott is about 887 ft thick in the Nankoweap Canyon area, the only area where the member was sampled. Here, 4 samples in the upper 2 dolomite beds were sampled for reservoir potential. Porosity of 4 samples ranged from 1.3 to 4.3% and averaged 2.45%. One sample, and perhaps 4 ft of section, had porosity of 3% or greater, the general productive minimum for carbonates.

Permeabilities of 4 samples ranked entirely in the poor to fair category, ranging from 0.02 to 0.56 md, and averaging 0.16 md. About 2 ft of the Nankoweap Canyon area section had a permeability greater than 0.5 md constituting Type I rock.

The TOC content of 32 samples ranged from 0.07 (poor) to 8.29% (excellent) and averaged 1.93% (good). About 773 ft of section rated as fair or better source rock (0.5% TOC or greater). Of this 773 ft, about 744 ft rated as good or better source rock (1.0% TOC or greater). Of this 744 ft, about 362 ft rated as very good or better source rock (2% TOC or greater). Of this 362 ft, about 127 ft rated as excellent source rock (4.0% TOC or greater).

Measured Tmax values ranged from 264 °C (immature) to 477 °C (condensate and wet gas window), and averaged 416 °C (immature). The eyeball best fit Tmax gradient line ranged from 425 °C (immature) at the top of the member, to 445 °C (early oil/peak oil boundary) at the base. This gradient places the upper 434 ft of the member in the immature maturity window, and the lower 453 ft of the member in the early oil window.

Sixtymile Formation

The Sixtymile Formation was only present and sampled in the Nankoweap Canyon

area, where it is 185 ft thick. One sample, S7, from the sandy uppermost 30 ft of the section, was analyzed for reservoir rock potential. This sample had 18.3% porosity (potentially productive for oil and gas in sandstones) and had 770 md of permeability (very good) putting it in the Type I rock category (greater than 0.5 md of permeability). Even though sample S7 had the highest porosity and highest permeability of any sample measured in the study, the basal 155 ft of the Sixtymile section consists of red, purple, tan, and cream siltstones considered to have little reservoir potential.

Seven samples of the Sixtymile Formation were analyzed for source rock potential. TOC's were entirely in the poor category, ranging from 0.03 to 0.06% and averaging 0.05%. No Tmax values were measured, however, based on the projected Tmax gradient curve from underlying data, the entire formation would be expected to be immature.

Tapeats Formation

The Tapeats Formation appeared to have no source rock potential and was not analyzed for source rock characteristics. In the Carbon Canyon area, the full Tapeats section was not sampled; only the basal 47.5 ft were. McKee (1945, p. 141-142) describes a nearby "section east of Lava Canyon, 4 miles south of Little Colorado" (River) which is a total of 300 ft thick. McKee's section would be about 1 mile south of our Carbon Canyon area section. The 5 samples from the basal 47.5 ft of the Tapeats Formation in the Carbon Canyon area section had porosities ranging from 5.0 to 11.6% and averaged 8.08%. About 32 of this 47.5 ft had porosities of 7% or greater, the general minimum for gas production in sandstones. About 25 of this 32 ft had porosities of 8% or greater, the general minimum for oil production in sandstones.

Permeabilities of 5 samples were entirely in the poor to fair category, ranging from 0.03 to 3.84 md, and averaging 1.19 md. About 19 ft of section had permeability greater than 0.5 md constituting Type I rock.

In the Nankoweap Canyon area, the entire 225 ft thick Tapeats section was measured, described, and sampled. Porosity of 8 samples ranged from 6.2 to 16.7% and averaged 11.59%. About 207 ft of section have porosities of 7% or greater, the general minimum for gas production in sandstones. About 202 of this 207 ft have porosities of 8% or greater, the general minimum for oil production in sandstones.

Permeabilities of 8 samples ranged from 0.40 (poor to fair) to 169 md (good), and averaged 38.03 md (moderate). About 205 ft of section had a permeability of 0.5 md or greater constituting Type I rock. About 121 ft of section had moderate or greater (15 md or greater) permeability, and about 42 of the 121 ft had good permeability (50 to 250 md).

Organic Richness Stratigraphic Summary

The TOC data in the present study do not support previous suggestions in the literature that the entire Chuar Group, approximately 6322 ft of section, are potential hydrocarbon source rocks. Only the 887 ft Walcott Member and the upper 165 to 390 ft of the Awatubi Member consistently have TOC's of fair or better. The members of the Galeros Formation have thin organically rich beds but these constitute a small proportion of the overall 3819 ft thickness of the formation. The following thicknesses of fair or better source rocks were estimated for the members of the Chuar Group: Tanner = 71 ft, Jupiter = 35 ft, Carbon Canyon = 63 to 86 ft, Duppa = 0 ft, Carbon Butte = 0 ft, Awatubi = 221 to 267 ft, Walcott = 773 ft. The Awatubi and Walcott are together about 1742 ft thick, and about 1040 ft or about 60% of these formations are fair or better source rock. The Galeros Formation is about 3819 ft thick, and about 192 ft or about 5% of this section is fair or better source rock. If the Duppa Member with no fair or better source rock is excluded, the remaining 3 Galeros members are 3179 ft thick and the 192 ft of fair or better source rock they contain constitutes 6% of their total thickness.

Maturity Stratigraphic Summary

The following maturity stratigraphic summary is based on the "eyeball" best fit of the Tmax maturity gradient (line) or its projection. Based on the Tmax maturity gradient, in the Nankoweap Canyon area, the Walcott Member is immature at the top and is at the early oil/peak oil boundary at the base. The Awatubi Member maturity is peak oil window at the top to late oil window at the base. The Carbon Butte Member is projected to be in the late oil window. The Duppa Member maturity is projected to be in the late oil window at the top to condensate and wet gas window at the base. The Carbon Canyon Member maturity is condensate and wet gas window at the top to dry gas window at the base. In this stratigraphic section the Jupiter and Tanner Members are projected to be in the dry gas window.

Based on the Tmax maturity gradient, in the Carbon Canyon area, the Walcott is projected to be immature, but was not sampled. The Awatubi Member maturity is immature at the top to early oil window at the base. The Carbon Butte maturity is projected to be early oil window at the top to peak oil window at the base. The Duppa Member maturity is projected to be peak oil window at the top to late oil window at the base. The Carbon Canyon Member maturity is late oil window at the top to condensate and wet gas window at the base. The Jupiter Member is in the condensate and wet gas window at the top and dry gas window at the base. The Tanner Member is in the dry gas window and the Nankoweap Formation is projected to be in the dry gas window.

The maturity gradient of the Nankoweap Canyon area appears to be higher than that

of the Carbon Canyon area. This appears to be true, not only in the Galeros Formation where some of the discrepancy could be due to margin of measurement error (error bars) around the very few actual data points, but it is also true for the Awatubi Formation where there are the most data points in both areas for a single member. However, it is the Awatubi gradient, not the average of the valid values which differs in the 2 areas, as will be discussed. In the Nankoweap Canyon area, the Awatubi Member maturity gradient ranges from peak oil to late oil windows. In the Carbon Canyon area, the Awatubi Member maturity gradient ranges from immature to early oil.

Since the Walcott and the upper 165 to 390 ft of the Awatubi are the significant Chuar Group source rock section, it is the maturity of these intervals that is critical to sourcing potential reservoirs in the Tapeats and Sixtymile Formations. In the Nankoweap Canyon area, the maturity gradient of these 2 intervals ranges from immature at the top to late oil at the base of the rich Awatubi (165 ft below the top). In the Carbon Canyon area, the maturity gradient of these 2 intervals ranges from immature (projected Walcott) to immature at the base of the rich Awatubi (390 ft below the top). The basal, less organically rich portion of the Awatubi Member does reach the early oil window at the base of the member.

Thus in the Nankoweap Canyon area, the significant Walcott to upper rich Awatubi source rock interval maturity gradient is immature to late oil, while, in the Carbon Canyon area, this entire interval is immature.

The first possible explanation for the higher Awatubi Member maturity gradient curve in the Nankoweap Canyon area than in the Carbon Canyon area is that the Awatubi gradient in the Nankoweap Canyon area is skewed higher, by the overlying Walcott Member average maturity which is greater than the average Awatubi maturity. The average Walcott Member maturity in the Nankoweap Canyon area of the 22 samples in the Tmax range considered valid (390 to 510 °C) is 433 °C (vs 428 °C for the Awatubi Member). The average Awatubi maturity in the Nankoweap Canyon area of the 4 samples considered valid (A25 = 427 °C, A25.5 = 428 °C, A26 = 435 °C, A28 = 422 °C) is 428 °C. The average Awatubi maturity in the Carbon Canyon area of the 9 samples in the valid range (SA8 = 393 °C, SA10 = 434 °C, SA11 = 438 °C, SA12 = 432 °C, SA13 = 429 °C, SA14 = 424 °C, SA17 = 431 °C, SA18 = 430 °C, SA20 = 430 °C) is 427 °C. The average of all Carbon Canyon area Awatubi samples in the upper 390 ft (rich source rock) is 412 °C and the average of all Nankoweap Canyon area Awatubi samples in the upper 165 ft (rich source rock) is 410 °C. Thus in both the Nankoweap Canyon area and the Carbon Canyon area the average Tmax valid Awatubi maturity is 1 or 2 °C apart; that is, very similar, while the Nankoweap Canyon area average Walcott Member maturity is 5 °C higher than the average Nankoweap Canyon area Awatubi maturity. This higher average maturity in the Nankoweap Canyon area Walcott shifts the Awatubi gradient toward higher values creating an apparent higher gradient than the actual average of the Awatubi values. If this is the explanation for the apparent disparity in the maturity gradient of the 2 areas, then it is unclear why the average

maturity of the Walcott Member is greater than that of the Awatubi Member at Nankoweap Canyon.

A second possible explanation for this maturity difference in the 2 areas may involve a different depth of burial history for the 2 areas. Sears (1990, p. 78-82) discusses a Late Precambrian extensional structural event which occurred during deposition of the Sixtymile Formation and which Elston and McKee (1982) called the Grand Canyon disturbance (Ford, 1990, p. 63). During this episode the Proterozoic section was rotated and faulted 5000 ft down to the west along the Butte Fault which set up a half graben preserving the Chuar Group on the west side of the fault (Sears, 1990, p. 82). This folding and block faulting was followed by a long period of erosion and peneplanation which produced the angular unconformity known as the "Great Unconformity" representing 230 million years, over which the Tapeats Formation was deposited (Middleton and Elliot, 1990, p. 86; Elston, 1989, p. 96-98). In the late Mesozoic to early Tertiary Laramide Orogeny the Butte Fault was reactivated with opposite movement (yo-yo tectonics) of 2700 ft of up to the west movement creating the East Kaibab monocline (Sears, 1990, p. 82). Thus there are at least 2 major periods of post-Chuar structural deformation affecting the area, the Grand Canyon disturbance and the Laramide orogeny. Ford and Breed (1973, Figure 1) map 3 northwest-southeast trending faults separating the Nankoweap and Carbon Canyon areas. Thus the higher maturity of the Nankoweap Canyon area than the Carbon Canyon area may be a result of deeper and/or longer burial of the former area.

A third possible explanation for the higher maturity of the Nankoweap Canyon area than the Carbon Canyon area may be a higher heat flow in the former area, perhaps associated with any of the 3 periods of volcanism or plutonism during the Cretaceous-Paleocene, Miocene, and Pliocene-Quaternary (Huntoon, 1989; Huntoon, 1990).

Summary of Nankoweap, Chuar Group, and Tapeats Reservoir Potential

The following thicknesses of potentially hydrocarbon productive porosity, based on the productive guidelines previously cited (3% for carbonates and 7% for clastics), were recognized in the Nankoweap through Tapeats Formations: Nankoweap = 130 ft, Tanner = 19 ft (only 29 of 64 ft of basal dolomite sampled), Jupiter = 6 ft, Carbon Canyon (2 samples: 20 ft and 10 - 15 ft each) = 35 ft maximum total, Duppa = 0 ft, Carbon Butte = 100 - 116 ft, Awatubi = 0 ft, Walcott = 4 ft, Sixtymile = 30 ft, Tapeats = 32 ft (only 47.5 out of probably 300 ft sampled in the Carbon Canyon area) to 207 ft.

These same units had the following thickness of greater than 0.5 md permeability in the Type I rock category: Nankoweap = 98 ft, Tanner = 3 ft (only 29 of 64 ft of the basal dolomite sampled), Jupiter = 0 ft, Carbon Canyon = 0 ft (2 samples only), Duppa = 0 ft, Carbon Butte = 44 or 77 to 144 ft, Awatubi = 0 ft, Walcott = 2 ft, Sixtymile = 30 ft (1 sample), Tapeats = 19 ft (only 47.5 out of probably 300 ft sampled in the Carbon Canyon

area) to 205 ft. Formational thicknesses ranking as moderate or greater in permeability are as follows: Nankoweap = 17 ft, Tanner = 0 ft, Jupiter = 0 ft, Carbon Canyon = 0 ft, Duppa = 0 ft, Carbon Butte = 0 - 4 ft, Awatubi = 0 ft, Walcott = 0 ft, Sixtymile = up to 30 ft (?), and Tapeats = 0 ft (only 47.5 out of probably 300 ft sampled in the Carbon Canyon area) to 121 ft.

Based on these results, significant reservoir potential, as measured by either potentially productive porosity or permeability, is present in the Nankoweap Formation (98-130 ft), Carbon Butte Member (44 or 77-144 ft), Sixtymile Formation (up to 30 ft), and Tapeats Formation (205-207 ft). Since these are outcrop samples, reservoir properties may have been altered by exposure, requiring caution in applying results directly to the subsurface, however, at least reservoir potential is indicated. Since the 887 ft Walcott Member and the upper 165 to 390 ft of the Awatubi Member are the significant source rocks identified in the present study, the overlying uppermost 30 ft of the Sixtymile Formation and the Tapeats Formation form likely reservoirs, which are ideally situated for hydrocarbon charging from below.

The Carbon Butte Member of the Kwagunt Formation and the Nankoweap Formation are possible reservoirs which could be sourced from either the 192 ft of source rock in the lower 3 members of the Galeros Formation or source rocks in the uppermost Awatubi and Walcott Members of the Kwagunt Formation where faulting, across the bounding fault of half graben, places the Carbon Butte or Nankoweap, on the upthrown side, against upper Awatubi or Walcott, on the downthrown side. Areal variation in the source richness of the Galeros Formation may enhance its organic richness and potential source thickness in areas away from of the Grand Canyon.

Organic Matter Type, Hydrocarbon Product Type, and Thermal Alteration Index (TAI)

The modified van Krevelen diagram shown in Figure 4 is not definitive as to kerogen type, apparently due to a fairly high maturity [probably at least greater than 0.5% Ro by comparison to Figures 5.1A and 5.2 of Peters and Cassa (1994, p. 96 and 97)] which results in the clustering points in the southwest corner of the diagram.

Figure 5 is a plot of Reactive Carbon Index [RCI = 10(S1 + S2)/TOC] vs. Productivity Index [PI = S1/(S1 + S2)]. Generally, Productivity Index indicates an immature maturity rank if less than 0.1, in the oil window if between 0.1 and 0.3, and in the gas window if greater than 0.3. Most points in the present study plot as immature or in the oil window (less than 0.3). Core Lab (Geochemical Well Profile, 1983) interpreted a Productivity Index (also called Transformation Ratio) of less than 0.3 to 0.4 as an indicator of indigenous hydrocarbons, and values of greater than 0.3 to 0.4 to indicate migrated oil. By this interpretation all but 1 of the samples in the present study would indicate the hydrocarbons measured by pyrolysis are indigenous to the source rocks being analyzed. In
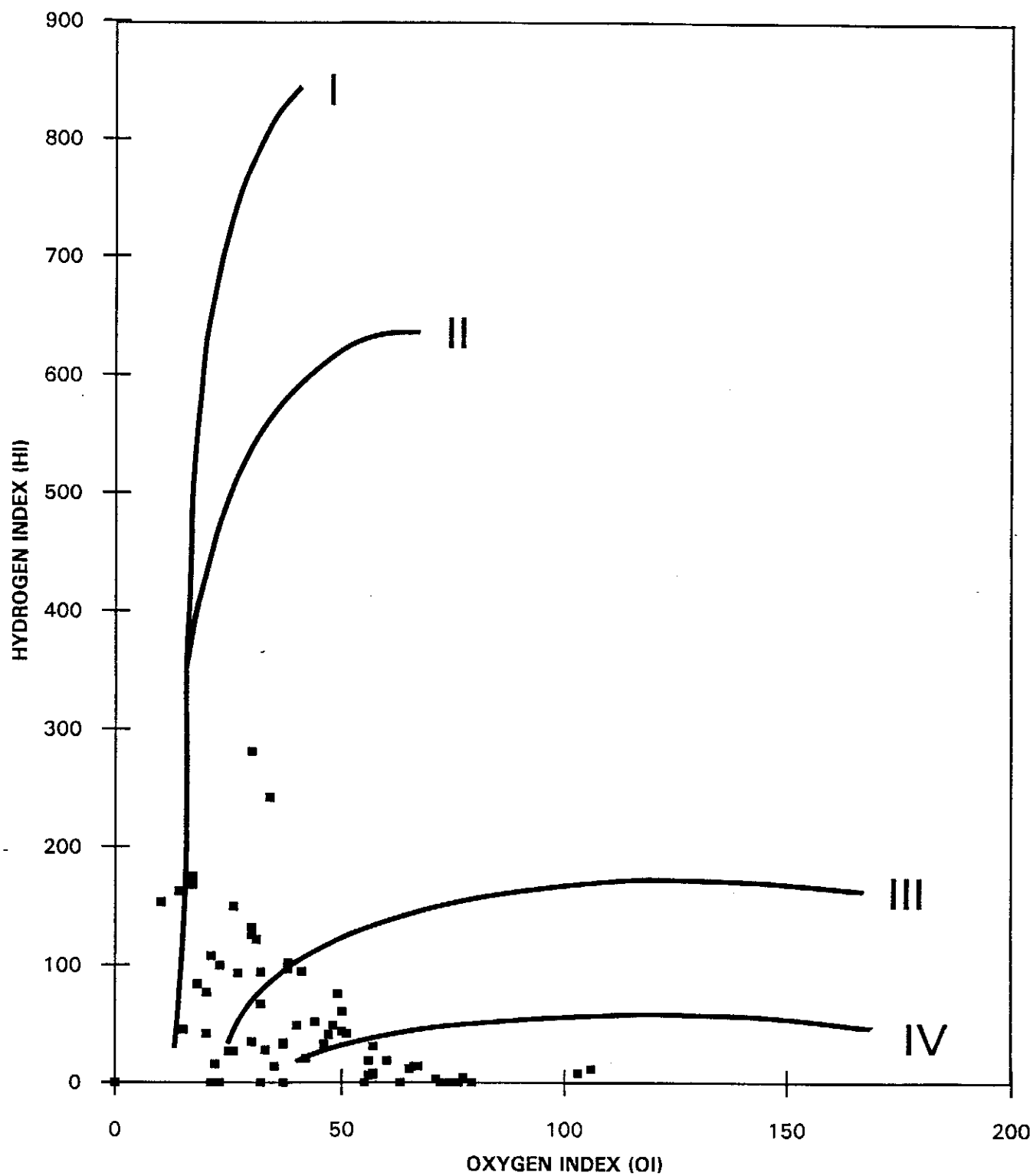
Figure 4. Modified van Krevelen diagram, Chuar samples, Nankoweap Canyon and Carbon Canyon Areas, Grand Canyon, Arizona.

addition, the RCI vs. PI cross-plot is used to indicate source rocks plotting in oil prone, gas prone, and uncertain intermediate areas. The samples of the present study plot in the gas prone and uncertain areas.

Organic Petrography by DGSI was used to attempt to identify the organic matter types in 31 samples. For each sample, organic petrography was conducted on whole rock plugs in reflected light, as well as on macerated kerogen concentrates in reflected and transmitted light. This was done to attempt to ascertain the nature of the organic material that was measured since true vitrinite did not exist in the Precambrian. "Vitrinite is derived from land plants and is not common in rocks older than Devonian because abundant land plants had not evolved yet" (Peters and Cassa, 1994, p. 101). Unstructured kerogen (lipids) makes up most of the organic matter in all of the samples. Minor amounts of vitrinite-like organic matter and solid bitumen occur as minor constituents amounting to at most 15% of the total organic fraction, but generally only being present as traces. Vitrinite-like particles fall into 2 types: elongate particles which are likely algal in origin, and round bodies which are most likely algal cysts, often present as infillings of microfossils. The majority of the reflectance measurements were made on the vitrinite-like particles. Solid bitumen occurs as pore filling or a pore lining. In a number of samples the distinction between vitrinite-like organic matter and solid bitumen was not clear cut, especially in the macerated samples as opposed to the whole rock samples. While the whole rock samples were better at distinguishing the organic matter type, the macerated samples were better for reflectance measurements and detecting fluorescence, due to failure of the whole rock samples to polish well and mineral matter fluorescence in the whole rock samples.

DGSI concluded that the solid organic matter had little or no fluorescence. Typically the unstructured kerogen (lipids) are in the massive or massive to micritized stage which goes along well with the lack of kerogen fluorescence. The thermal alteration index (TAI) data on the kerogen is quite uniform: 3 (condensate and wet gas according to DGSI, this study; late oil according to Peters and Cassa, 1994, p. 96, Table 5.3) or 3 to 3+ (condensate and wet gas to dry gas according to DGSI, this study; late oil (to postmature?) according to Peters and Cassa, 1994, p. 96, Table 5.3). One sample (SA20, Awatubi Member in the Carbon Canyon area) has a TAI of 2 (oil window according to DGSI, this study; immature according to Peters and Cassa, 1994, p. 96, Table 5.3) to 3.

Comparison of Tmax and Organic Petrologic Maturity Indicators

The organic maturity interpretations in this study are based primarily on Tmax data because this was the maturity data set which was available for the greatest number of samples. A total of 53 samples had Tmax values and of these, 40 samples with Tmax values in the 390 to 520 °C range were used to construct the 2 Tmax gradient curves (Plates 1 and 2) which were the basis for interpretation. For comparison, only 27 samples had Ro
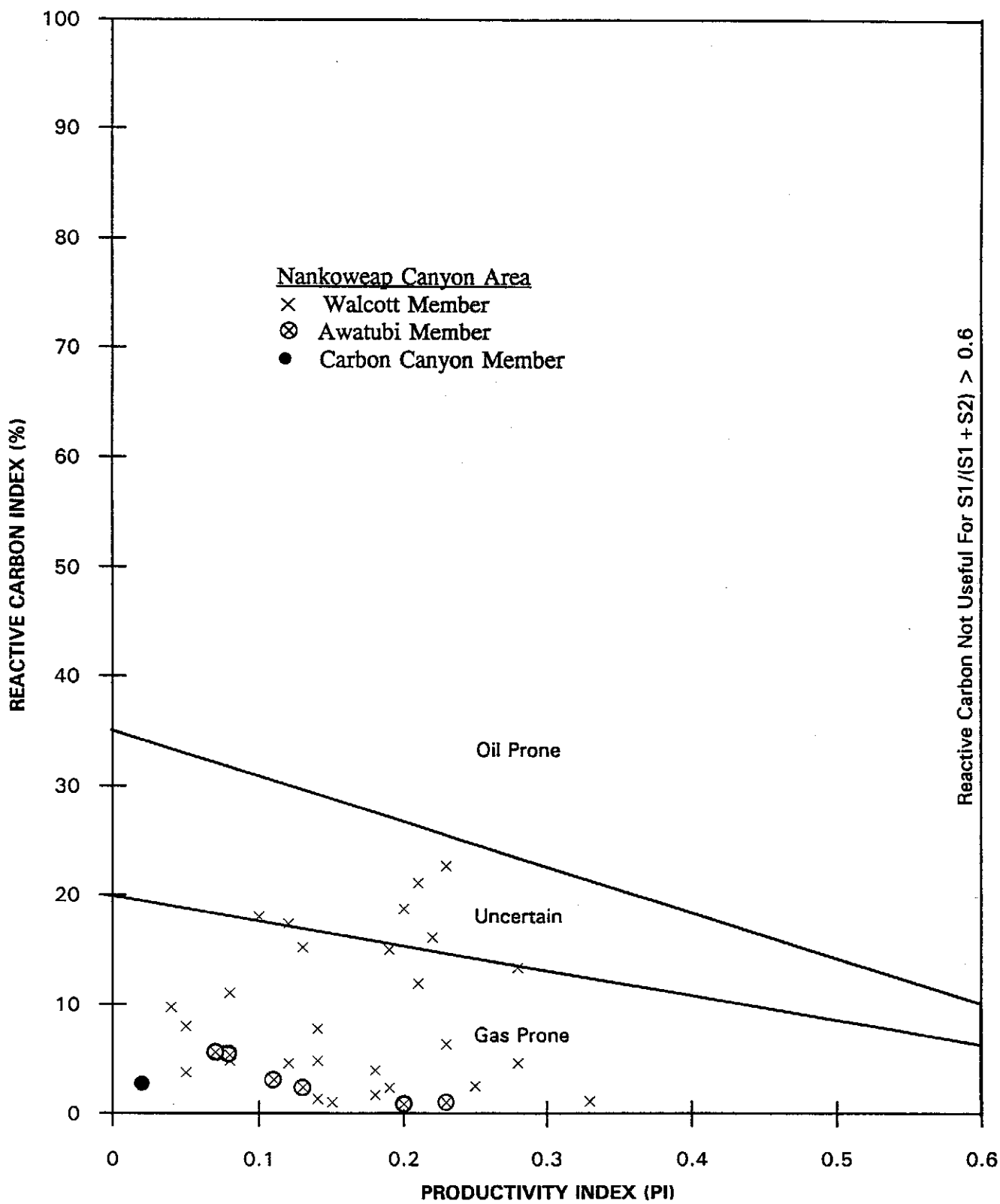
Figure 5a. Crossplot of Reactive Carbon Index vs. Productivity Index with Kerogen Type, Nankoweap Canyon Area.
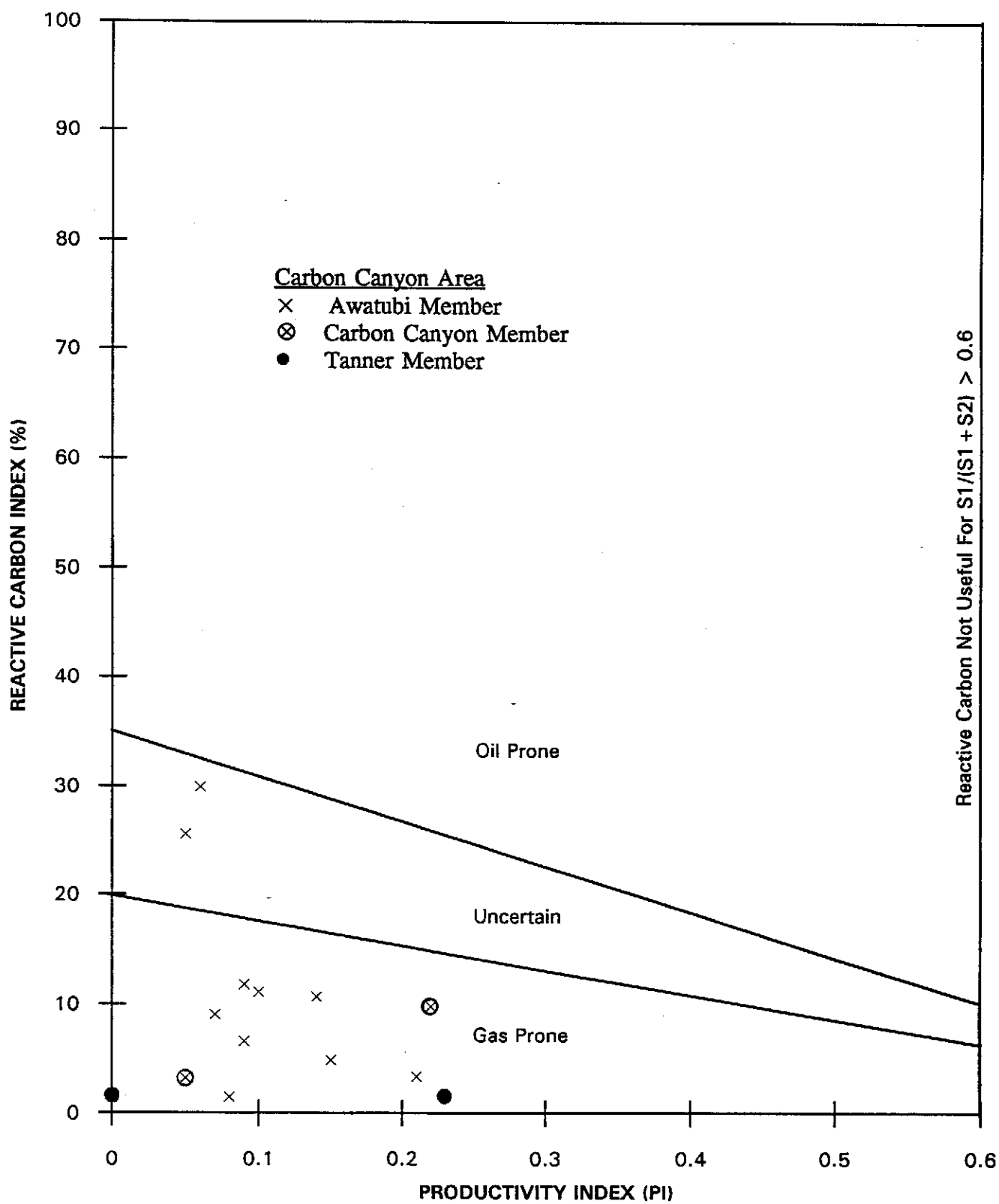
Figure 5b. Crossplot of Reactive Carbon Index vs. Productivity Index with Kerogen Type, Carbon Canyon Area.

(reflectance in oil) measurements on either vitrinite-like material (designated "Ro-(O)" for "other" in Table 4) or bitumen (designated "Ro-(B)" for "bitumen" in Table 4). Twenty-five samples had TAI estimates of color values of unstructured lipids and 31 samples had fluorescence intensity estimates of unstructured lipids. DGSI used Landis and Castano's calibration chart to convert measured reflectance of bitumen [Ro-(B)] to an estimated vitrinite reflectance equivalent (VRE). An estimated VRE was available for 14 samples.

Jacob and others (1981) derived a formula for converting bitumen reflectance (Rb) to an equivalent vitrinite reflectance (Rv) from a study of worldwide bitumen deposits (Gentzis and Goodzari, 1990). Using this linear equation, $Rv = 0.618(Rb) + 0.4$, to convert Grand Canyon bitumen reflectance values to equivalent vitrinite reflectance values results in uniformly lower values than the VRE values of DGSI, which are derived from Landis and Castano's calibration chart (see Table 4).

DGSI noted that in the current sample set the correlation between Ro and Tmax is not strong. This contrasted with results of Pawlewicz and Palacas (1992), who stated that their reflectance measurements on the vitrinite-like organic matter in the Precambrian correlated well with Rock-Eval pyrolysis Tmax values. In order to determine if Tmax maturity estimates consistently differ from those of the other maturity indicators, the available measured and interpreted maturity indicators were compared in Table 4 and Figure 6. Figure 6 shows 7 maturity, or hydrocarbon generation, zones at the top: immature, early oil, peak oil, late oil, condensate and wet gas, dry gas, and burned out for gas. It also shows the values separating each maturity zone for 4 maturity indicators: Ro, Tmax, TAI, and fluorescence. The maturity zone delimiting values for both Ro and Tmax are from Peters and Cassa (1994, p. 94 and 96, Table 5.3). For TAI the maturity zone delimiting values are slightly higher in the conversions of DGSI as compared to the conversions of Peters and Cassa (1994, p. 96, Table 5.3) and Wapples (1980, p. 919 and 921). As a result, there are 2 TAI to maturity zone conversions shown in Figure 6. Van Gijzel (1982, p. 159 and 168) noted that sporinite and alginite fluorescence is extinguished between a vitrinite reflectance of 1.20% and 1.35%. This marks the "oil death line (zone)" above which only wet or dry gas occur if not entirely burned out for gas. Thus lack of fluorescence indicates a maturity equivalent to an Ro of 1.20% or greater. Two sets of organic petrographic measurements were made for each stratigraphic sample. One set of measurements was on the whole rock (WR) sample and a second set of measurements was made on a macerated kerogen concentrate (K) sample. Figure 6 shows 7 rows for each of these (whole rock and macerated kerogen concentrate samples). These rows are as follows: (1a) is the vitrinite reflectance equivalent (VRE) converted from the measured bitumen Ro using Landis and Castano's calibration chart; (1b) is the measured mean bitumen reflectance [Ro-(B)]; (1c) is the measured mean vitrinite-like reflectance [Ro-(O)]; (2) is the Tmax; (3) is the TAI converted to maturity zones using the delimiting values of DGSI; (4) is the TAI converted to maturity zones using the delimiting values of Peters and Cassa (1994) and Waples (1980); and (5) is the extinction of sporinite and alginate fluorescence indicating an Ro of 1.20 or greater. If

TABLE 4. COMPARISON OF Tmax AND ORGANIC PETROLOGIC MATURITY INDICATORS
(WR=whole rock sample; K=macerated sample; (B)=bitumen; (O)=other; N.D.=not determinable)

Sample	DGSI VRE	Jacob* VRE	Ro-(B)	Ro-(O)	Tmax°C	TAI	Fluor	Note
NANKOWEAP CANYON AREA								
W41-WR	-	-	-	1.22	434	-	0	
W41-K	-	-	-	1.35	434	3+	0	
W39-WR	-	-	-	-	429	-	0	
W39-K	-	-	-	1.03	429	3+	1	
W38-WR	-	-	-	-	427	-	1	
W38-K	-	-	-	-	427	3(B),3+(O)	0	
W33-WR	-	-	-	-	432	-	1	
W33-K	1.41?	1.09	1.12?	1.17?	432	-	0	
W32-WR	-	-	-	-	428	-	N.D.	
W32-K	-	-	-	-	428	-	0(B),1(O)	
W30-WR	-	-	-	-	431	-	N.D.	
W30-K	1.28	1.01	0.98	1.16?	431	-	0	
W26-WR	-	-	-	-	424	-	0	
W26-K	1.06?	0.86	0.75?	-	424	3	0(B),1(O)	
W18-WR	-	-	-	-	424	-	0	
W18-K	-	-	-	-	424	3	0	
W17-WR	1.27	1.01	0.98	-	441	-	0	
W17-K	1.30	1.02	1.00	1.09	441	3	1	
W16-WR	-	-	-	-	431	-	N.D.	
W16-K	-	-	-	-	431	3	0(B),1(O)	
W15-WR	-	-	-	0.98?	432	-	0	
W15-K	-	-	-	0.64	432	3	0(B),1(O)	
W13-WR	-	-	-	-	434	-	0	
W13-K	1.07?	0.88	0.77?	0.88?	434	3	0(B),1(O)	
W12-WR	-	-	-	0.67?	422	-	?	
W12-K	-	-	-	-	422	N.D.	0	
W10-WR	0.93?	0.78	0.62?	-	428	-	?	
W10-K	1.02?	0.84	0.71?	1.36?	428	3	0(B),1(O)	
W05-WR	-	-	-	1.03	429	-	N.D.	
W05-K	-	-	-	1.18	429	3	0	
W02-WR	-	-	-	-	439	-	0	
W02-K	1.17?	0.94	0.87?	1.00	439	3(B),3+(O)	0(B),1(O)	

*Jacob and others, 1981

TABLE 4. COMPARISON OF Tmax AND ORGANIC PETROLOGIC MATURITY INDICATORS
(WR=whole rock sample; K=macerated sample; (B)=bitumen; (O)=other; N.D.=not determinable)

Sample	DGSI VRE	Jacob* VRE	Ro-(B)	Ro-(O)	Tmax°C	TAI	Fluor	Note
				NANKOWEAP CANYON AREA (continued)				
A28-WR	0.80	0.70	0.48	0.61	422	-	0	
A28-K	-	-	-	0.76?	422	N.D.	0	
A26-WR	-	-	-	0.88	435	-	0	
A26-K	-	-	-	0.90	435	3	0	
A25.5-WR	1.07	0.88	0.77	0.97	428	-	0	rich
A25.5-K	-	-	-	0.95	428	N.D.	0	Awatubi
04-WR	1.82	1.36	1.56	1.74	497	3	0	
04-K	-	-	-	1.53	497	-	0	
CC1-WR	2.11	1.55	1.86	-	482	-	0	
CC1-K	2.28	1.66	2.04	-	482	3(B),3+(O)	0	
				CARBON CANYON AREA				
SA20-WR	-	-	-	0.58?	430	-	0	
SA20-K	-	-	-	0.46?	430	2(B),3(O)	1	
SA18-WR	-	-	-	0.63?	430	-	N.D.	
SA18-K	-	-	-	0.57?	430	3	0	
SA17-WR	-	-	-	0.59?	431	-	0	
SA17-K	-	-	-	0.59	431	3	1	
SA13-WR	-	-	-	0.63?	429	-	0	
SA13-K	-	-	-	0.70	429	3	0(B),1(O)	
SA12-WR	1.20?	0.96	0.90?	0.82?	432	-	0	
SA12-K	-	-	-	0.64	432	3	0(B),1(O)	
SA10-WR	-	-	-	1.02	434	-	0	
SA10-K	-	-	-	0.96	434	3	0(B),1(O)	
SA08-WR	-	-	-	0.89	393	-	0	rich
SA08-K	-	-	-	0.80	393	3	0(B),1(O)	Awatubi
SCC50-WR	-	-	-	1.10?	464	-	0	
SCC50-K	-	-	-	1.06?	464	3	0	
SCCX1-WR	-	-	-	-	449	-	0	
SCCX1-K	1.65?	1.25	1.37?	1.35	449	3(B),3+(O)	0	
ST04-WR	1.99	1.47	1.73	1.79	515	-	0	
ST04-K	2.10	1.54	1.85	1.92	515	3+	0	

*Jacob and others, 1981

INDICATORS		HYDROCARBON GENERATION ZONES						
		IMMATURE	EARLY OIL	PEAK OIL	LATE OIL	COND & WET GAS	DRY GAS	BURNED OUT
1 - Ro (%)	0.2	0.6	0.65	0.9	1.35	2.0	4.0	
2 - Tmax (°C)		435	445	450	470	500?	550+	
3 - TAI (dgsi)		2-	2	2+	3-	3+	4+	
4 - TAI (p&c,w)	1.5	2.6	2.7	2.9	3.3	3.7	4.0	
5 - Fluor. (vg)					Ro=1.20 ↔ Ro=1.35 = Extinction of sporinite Fluorescence			

Sample

W41-WR

W41-K

W39-WR

W39-K

W38-WR

W38-K

W33-WR

W33-K

W32-WR

W32-K

W30-WR

W30-K

Figure 6a. Graph of Tmax and organic petrologic maturity indicators for whole rock and macerated kerogen concentrates, Nankoweap Canyon Area, Grand Canyon, Arizona.

INDICATORS	HYDROCARBON GENERATION ZONES						
	IMMATURE	EARLY OIL	PEAK OIL	LATE OIL	COND & WET GAS	DRY GAS	BURNED OUT
1 - Ro (%)	0.2 ... 0.6	0.65	0.9	1.35	2.0	4.0	
2 - Tmax (°C)	435	445	450	470	500?	550+	
3 - TAI (dgsi)	2-	2	2+	3-	3+	4+	
4 - TAI (p&c,w)	1.5	2.6	2.7	2.9	3.3	3.7	4.0
5 - Fluor. (vg)				Ro=1.20 ⟷ Ro=1.35 = Extinction of sporinite Fluorescence			

Sample
W26-WR
W26-K
W18-WR
W18-K
W17-WR
W17-K
W16-WR
W16-K
W15-WR
W15-K
W13-WR
W13-K

Figure 6a. Graph of Tmax and organic petrologic maturity indicators for whole rock and macerated kerogen concentrates, Nankoweap Canyon Area, Grand Canyon, Arizona. (continued)

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INDICATORS	HYDROCARBON GENERATION ZONES						
	IMMATURE	EARLY OIL	PEAK OIL	LATE OIL	COND & WET GAS	DRY GAS	BURNED OUT
1 - Ro (%)	0.2	0.6	0.65	0.9	1.35	2.0	4.0
2 - Tmax (°C)		435	445	450	470	500?	550+
3 - TAI (dgsi)		2-	2	2+	3-	3+	4+
4 - TAI (p&c,w)	1.5	2.6	2.7	2.9	3.3	3.7	4.0
5 - Fluor. (vg)				Ro=1.20 ←→ Ro=1.35 = Extinction of sporinite Fluorescence			

Sample
W12-WR
W12-K
W10-WR
W10-K
W05-WR
W05-K
W02-WR
W02-K
W28-WR
W28-K
W26-WR
W26-K

Figure 6a. Graph of Tmax and organic petrologic maturity indicators for whole rock and macerated kerogen concentrates, Nankoweap Canyon Area, Grand Canyon, Arizona. (continued)

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Figure 6a. Graph of Tmax and organic petrologic maturity indicators for whole rock and macerated kerogen concentrates, Nankoweap Canyon Area, Grand Canyon, Arizona. (continued)

INDICATORS	HYDROCARBON GENERATION ZONES						
	IMMATURE	EARLY OIL	PEAK OIL	LATE OIL	COND & WET GAS	DRY GAS	BURNED OUT
1 - Ro (%)	0.2 0.6	0.65	0.9	1.35	2.0	4.0	
2 - Tmax (°C)	435	445	450	470	500?	530+	
3 - TAI (dgsi)	2-	2	2+	3-	3+	4+	
4 - TAI (p&c,w)	1.5 2.6	2.7	2.9	3.3	3.7	4.0	
5 - Fluor. (vg)				Ro=1.20 ↔ Ro=1.35 = Extinction of sporinite Fluorescence			

Sample

SA20-WR
SA20-K
SA18-WR
SA18-K
SA17-WR
SA17-K
SA13-WR
SA13-K
SA12-WR
SA12-K
SA10-WR
SA10-K

Figure 6b. Graph of Tmax and organic petrologic maturity indicators for whole rock and macerated kerogen concentrates, Carbon Canyon Area, Grand Canyon, Arizona.

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INDICATORS	HYDROCARBON GENERATION ZONES						
	IMMATURE	EARLY OIL	PEAK OIL	LATE OIL	COND & WET GAS	DRY GAS	BURNED OUT
1 - Ro (%)	0.2	0.6	0.65	0.9	1.35	2.0	4.0
2 - Tmax (°C)		435	445	450	470	500?	550+
3 - TAI (dgsi)		2-	2	2+	3-	3+	4+
4 - TAI (p&c,w)	1.5	2.6	2.7	2.9	3.3	3.7	4.0
5 - Fluor. (vg)				Ro=1.20 ←→ Ro=1.35 = Extinction of sporinite Fluorescence			

Sample

SA08-WR

SA08-K

SCC50-WR

SCC50-K

SCCX1-WR

SCCX1-K

ST04-WR

ST04-K

Figure 6b. Graph of Tmax and organic petrologic maturity indicators for whole rock and macerated kerogen concentrates, Carbon Canyon Area, Grand Canyon, Arizona. (continued)

any sample fluorescence is noted, the row is not scored for that sample. The Tmax maturity is shown in dashed line while maturity from organic petrologic sources is shown in solid line.

In 22 of the 31 samples (71%), Tmax maturity was lower than all of the other (organic petrologic) indicators. This discrepancy appears to be most pronounced for the more immature samples, perhaps due to the narrower Ro range of the early and peak oil zones as compared to zones of higher maturity. This discrepancy suggests either: (1) that the true maturity of the samples may be higher than that suggested by the interpretation based on Tmax, or (2) that Tmax maturity is correct and that weathering or other causes have produced an apparent increase in the maturity of the organic petrology indicators (Ro, TAI, fluorescence). DGSI noted that iron oxide alteration was seen in a number of whole rock samples and moderate to strong alteration may alter some of the geochemical data. DGSI also noted that maturity can be affected by weathering, oxidation, bitumen saturation, or coking. Weathering, bitumen admixed with the unstructured material, and micrinization can darken the kerogen and raise the TAI value. A third alternative to explain the discrepancy involves the extreme age of the Chuar rocks and is based on the fact that maturation is a function of time and temperature. The higher effective maturity indicated by the organic petrology may have been achieved at these lower than usual Tmax temperatures due to the extra 235 million years that the Chuar source rocks have been maturing relative to the usual Phanerozoic (543 million years or younger) source rocks. This alternative was suggested by Geoffrey S. Bayliss, Geochem Laboratories, Inc., Houston, Texas, in work prepared for, and made available to the authors by, Ben Donegan of Albuquerque, New Mexico. A fourth possible explanation of the discrepancy may involve unusual geochemical maturation pathways of the simpler Proterozoic life-forms.

Based on the petrologic indicators, in the Nankoweap Canyon area, most of the Walcott Member samples are in the peak oil to condensate and wet gas windows. Most of the Awatubi Member samples are in the peak oil to condensate and wet gas windows, but range from immature to dry gas. All samples examined petrologically were in the rich upper 165 ft of the member. The Carbon Canyon Member samples were mostly in the condensate/wet gas window, but ranged from late oil to dry gas windows.

Based on the petrologic indicators, in the Carbon Canyon area, most of the Awatubi Member samples, all of which were from the rich upper 390 ft of the member, were mostly in the immature to condensate/wet gas windows. The Carbon Canyon Member samples were mostly in the late oil to condensate/wet gas windows. The single sample from the Tanner Member petrologic maturity indicators ranged from late oil to dry gas windows.

As noted above, only 1 point from either of the 2 areas (Nankoweap Canyon or Carbon Canyon) had a Productivity Index greater than 0.3 (gas window). All other points had lower values indicative of the immature or oil windows.

Depositional Environments

Carbon Butte Member of Kwagunt Formation

The Carbon Butte Sandstone shows distinct evidence of having been deposited under the influence of tidal forces and thereby having a shallow marine origin. Opposing crossbedding (north and south) indicates reversing currents and locally well developed sigmoidal crossbedding is characteristically produced by bedform migration under unequal reversing flow. Symmetric (wave) ripple marks in the upper part of the unit support a shallow water interpretation. The presence of multiple channels in the lower part, combined with mud chip conglomerates, argue for a setting in which tidal channels cut into associated muddy deposits. The thickness and laterally extensive distribution of the unit suggests deposition in a very large estuary or a tidal seaway.

Tapeats Formation

The entire Tapeats Sandstone has been interpreted as a transgressive shallow marine deposit (Mckee, 1945), but the exposures in Nankoweap and Carbon Canyons appear largely to be of a nonmarine origin, particularly near the base. The uniformity of cross-bedding dip directions (toward the west), the lack of segregation of pebbles and sand typical of wave winnowing, and the lack of vertical trends indicative of shoreline sand successions or meandering streams argues for deposition in a fluvial braid plain environment. There is no question that elsewhere in the Canyon, the Tapeats contains trace fossils indicative of a marine setting (as at the confluence of the Colorado and Little Colorado Rivers), but these typically lie in the upper, "transitional" part of the section (McKee, 1945). We accept the Tapeats transgression postulated by McKee (1945), but feel that the initial Cambrian deposition, at least locally, began on a fluvial braid plain, as opposed to an offshore marine environment, as he envisioned. Hereford (1977) and Middleton and Hereford (1981) also interpreted the Tapeats to consist of basal fluvial facies overlain by a variety of nearshore marine facies in north-central Arizona.

Tanner, Carbon Canyon, Awatubi, and Walcott Member Shales

Thirty shale samples were analyzed for compositional data with respect to saturate hydrocarbons, aromatic hydrocarbons, resins (nitrogen, sulfur, and oxygen compounds), and asphaltenes using liquid chromatography (Table 5 and Figure 7). Samples were from both the Nankoweap Canyon area (NCA) and the Carbon Canyon area (CCA). Included in the 30 samples were 16 NCA Walcott Member samples, 7 CCA Awatubi Member samples, 3 NCA Awatubi Member samples, 2 CCA Carbon Canyon Member samples, 1 NCA Carbon Canyon

Member sample, and 1 CCA Tanner Member sample. These same 30 samples were also analyzed (see Table 6) for stable carbon isotope ratios (del C13 of the Saturate fraction and del C13 of the Aromatic fraction). Figure 8 shows the plot of del C13 Aromatic on the vertical axis vs. del C13 Saturate on the horizontal axis. Points lying in the southeast diagonal half of this plot tend to be marine in origin, while points plotting in the northwest diagonal half of this plot tend to be nonmarine in origin. Figure 8 indicates that the shales from the Tanner, Carbon Canyon, Awatubi, and Walcott Members all lie in the southeast diagonal half suggesting marine deposition. This supports Cook's (1991) suggested depositional environment for the Walcott Member, namely deposition on a shallow carbonate ramp within a marine embayment, in contrast to the suggestion by Reynolds and Elston (1986) that the Chuar Group was deposited in a sediment-starved lacustrine environment.

Geographic Distribution of the Chuar Group in Wells

In addition to stratigraphic distribution of potential source rock, the geographic distribution of these rocks is also a critical uncertainty in petroleum exploration. Uncertainties relating to geographic distribution include: (1) presence, absence, or thickness variations related to depositional basin geometry; (2) preservation, complete erosional removal, or thinning related to preservational basin geometry and the sub-Tapeats Formation "Great Unconformity"; and (3) variations in source richness related to depositional environment and biofacies and lithofacies variations.

In the northern Arizona and southern Utah area, northward to about Township 22 South in Utah, only 4 wells penetrating Precambrian sediments are known. The Tidewater No. 1 Kaibab Gulch Unit well (34-42s-2w, Kane Co., Utah) reached a total depth of 6253 ft in probable Chuar Group sediments. It penetrated the Tapeats Formation at 4865 ft, redbeds which may be the Precambrian Sixtymile Formation at 5113 ft, and gray shales of probable Chuar Group at 5313 ft. A total of 1140 ft of Precambrian sediments were seen in the well. Sample cuttings and a geochemical analysis are available from the U.S. Geological Survey Core Repository at the Denver Federal Center, Denver, Colorado. The organic richness of the Chuar Group shales in this well was considerably poorer than in the Grand Canyon, with a TOC range of 0.12 (poor) to 0.52% (fair), and averaging 0.3% (poor). If these shales correlate with the Walcott or uppermost Awatubi Members in the upper part of the Chuar Group, then the lower organic richness here suggests we are seeing an areal variation in source richness. However, the other equally likely explanation is that the "Great Unconformity" at the base of the Tapeats has here cut into the lower Awatubi Member of the Kwagunt Formation or the Galeros Formation and these values in the Tidewater well are consistent with those of these lower Chuar members in the Grand Canyon.

The Rangeland Petroleum No. 1 Judd Hollow well (19-43s-2e, Kane Co., Utah) reached a total depth of 9012 ft in possible Chuar Group shales. The top of the Tapeats

TABLE 5. COMPOSITIONAL DATA

Field Sample	DGSI #	Samp wt. Used (g)	Sat(g)	Sat(%)	Compositional Aro(g)	Aro(%)	NSO(g)	NSO(%)	Asph(g)	Asph(%)	Total Recovery (g)	Total Recovery (%)	Deasphaltene Weight (g)
Nankoweap Canyon Area													
W41	uso31645	0.0021	0.0005	25.0	0.0002	10.0	0.0011	55.0	0.0002	10.0	0.0020	95.2	0.0019
W39	uso31643	0.0061	0.0021	42.9	0.0010	20.4	0.0018	36.7	0.0000	0.0	0.0049	80.3	0.0061
W38	uso31642	0.0352	0.0116	61.1	0.0031	16.3	0.0037	19.5	0.0006	3.2	0.0190	54.0	0.0346
W33	uso31637	0.0204	0.0092	65.2	0.0024	17.0	0.0023	16.3	0.0002	1.4	0.0141	69.1	0.0202
W32	uso31636	0.0419	0.0160	61.3	0.0050	19.2	0.0048	18.4	0.0003	1.1	0.0261	62.3	0.0416
W30	uso31635	0.0252	0.0113	57.9	0.0041	21.0	0.0039	20.0	0.0002	1.0	0.0195	77.4	0.0250
W26	uso31634	0.0299	0.0171	76.0	0.0031	13.8	0.0022	9.8	0.0001	0.4	0.0225	75.3	0.0298
W18	uso31631	0.0291	0.0165	47.7	0.0024	10.9	0.0030	13.6	0.0002	0.9	0.0221	75.9	0.0289
W17	uso31630	0.0497	0.0130	32.8	0.0161	40.7	0.0058	14.6	0.0047	11.9	0.0396	79.7	0.0450
W16	uso31629	0.0499	0.0230	54.0	0.0165	38.7	0.0027	6.3	0.0004	0.9	0.0426	85.4	0.0495
W15	uso31628	0.0271	0.0139	60.4	0.0060	26.1	0.0029	12.6	0.0002	0.9	0.0230	84.9	0.0269
W13	uso31626	0.0482	0.0263	66.6	0.0096	24.3	0.0035	8.9	0.0001	0.3	0.0395	82.0	0.0481
W12	uso31625	0.0196	0.0099	63.1	0.0034	21.7	0.0024	15.3	0.0000	0.0	0.0157	80.1	0.0196
W10	uso31623	0.0172	0.0089	60.5	0.0035	23.8	0.0023	15.6	0.0000	0.0	0.0147	85.5	0.0172
W05	uso31618	0.0121	0.0051	49.5	0.0031	30.1	0.0020	19.4	0.0001	1.0	0.0103	85.1	0.0120
W02	uso31615	0.0087	0.0038	49.4	0.0023	29.9	0.0014	18.2	0.0002	2.6	0.0077	88.5	0.0085
A28	uso31580	0.0060	0.0031	56.4	0.0006	10.9	0.0018	32.7	0.0000	0.0	0.0055	91.7	0.0060
A26	uso31578	0.0056	0.0021	42.9	0.0007	14.3	0.0021	42.9	0.0000	0.0	0.0049	87.5	0.0056
A25.5	uso31577	0.0052	0.0018	46.2	0.0004	10.3	0.0017	43.6	0.0000	0.0	0.0039	75.0	0.0052
CC1	uso31679	0.0017	0.0001	5.9	0.0004	23.5	0.0010	58.8	0.0002	11.8	0.0017	100.0	0.0015
Carbon Canyon Area													
SA20	uso31699	0.0189	0.0060	44.1	0.0030	22.1	0.0044	32.4	0.0002	1.5	0.0136	72.0	0.0187
SA18	uso31697	0.0079	0.0023	33.3	0.0013	18.8	0.0031	44.9	0.0002	2.9	0.0069	87.3	0.0077
SA17	uso31696	0.0040	0.0013	34.2	0.0007	18.4	0.0018	47.4	0.0000	0.0	0.0038	95.0	0.0040
SA13	uso31692	0.0043	0.0019	44.2	0.0006	14.0	0.0018	41.9	0.0000	0.0	0.0043	100.0	0.0043
SA12	uso31691	0.0060	0.0030	55.6	0.0009	16.7	0.0015	27.8	0.0000	0.0	0.0054	90.0	0.0060
SA10	uso31689	0.0056	0.0008	33.3	0.0004	16.7	0.0012	50.0	0.0000	0.0	0.0024	42.9	0.0056
SA08	uso31687	0.0036	0.0016	50.0	0.0004	12.5	0.0012	37.5	0.0000	0.0	0.0032	88.9	0.0036
SCC50	uso31546	0.0011	0.0001	10.0	0.0003	30.0	0.0005	50.0	0.0001	10.0	0.0010	90.9	0.0010
SCCX1	uso31678	0.0092	0.0047	67.1	0.0008	11.4	0.0013	18.6	0.0002	2.9	0.0070	76.1	0.0090
ST04	uso31655	0.0004	0.0001	20.0	0.0002	40.0	0.0001	20.0	0.0001	20.0	0.0005	100.0	0.0003

Sat = saturate hydrocarbons; Aro = aromatic hydrocarbons; NSO = nitrogen, sulfur, and oxygen compounds (resins); Asph = asphaltenes
Sample weight used = sample weight in grams of the material used for the liquid chromatography procedure.
Total Recovery (g) = total combined weight in grams of the saturate, aromatic, NSO, and asphaltene fractions.
Deasphaltene weight = weight in grams of the "sample weight used" minus the asphaltene weight.

Figure 7. Compositional Data

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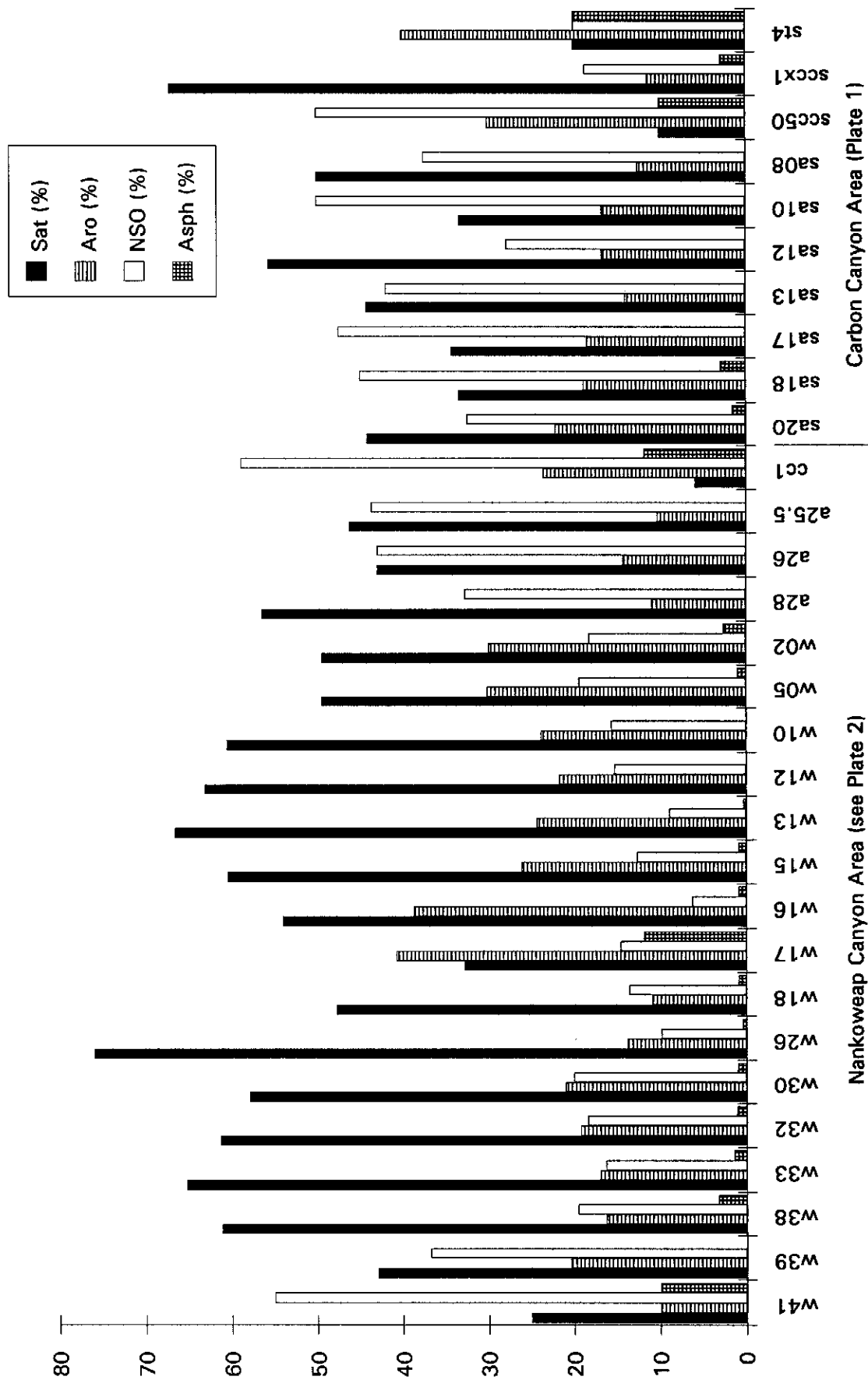
TABLE 6. STABLE CARBON ISOTOPE DATA

Field Sample	DGSI #	del C13 Sat	del C13 Aro	% Total Sulfur	Nickel (ppm)	Vanadium (ppm)
Nankoweap Canyon Area						
W41	uso31645	-26.2	-26.3	na	na	na
W39	uso31643	-26.0	-26.4	na	na	na
W38	uso31642	-26.8	-26.8	na	na	na
W33	uso31637	-26.5	-26.8	na	na	na
W32	uso31636	-26.4	-26.9	na	na	na
W30	uso31635	-26.0	-26.1	na	na	na
W26	uso31634	-25.5	-27.3	na	na	na
W18	uso31631	-24.6	-24.8	na	na	na
W17	uso31630	-25.3	-25.1	na	na	na
W16	uso31629	-25.6	-25.6	na	na	na
W15	uso31628	-25.6	-25.9	na	na	na
W13	uso31626	-26.4	-26.0	na	na	na
W12	uso31625	-26.4	-26.2	na	na	na
W10	uso31623	-26.6	-26.4	na	na	na
W05	uso31618	-25.7	-25.8	na	na	na
W02	uso31615	-27.4	-26.6	na	na	na
A28	uso31580	-24.7	-25.1	na	na	na
A26	uso31578	-22.4	-23.4	na	na	na
A25.5	uso31577	-18.6	-20.7	na	na	na
CC1	uso31679	-25.3	-25.3	na	na	na
Carbon Canyon Area						
SA20	uso31699	-22.4	-21.7	na	na	na
SA18	uso31697	-22.3	-21.8	na	na	na
SA17	uso31696	-18.7	-19.5	na	na	na
SA13	uso31692	-15.2	-16.8	na	na	na
SA12	uso31691	-18.6	-19.0	na	na	na
SA10	uso31689	-12.6	-15.0	na	na	na
SA08	uso31687	-16.7	-19.2	na	na	na
SCC50	uso31546	-25.8	-26.6	na	na	na
SCCX1	uso31678	-26.2	-25.8	na	na	na
ST04	uso31655	-27.5	-27.2	na	na	na

*Sat = saturate hydrocarbons; Aro = aromatic hydrocarbons

Stable Carbon Isotope Ratios
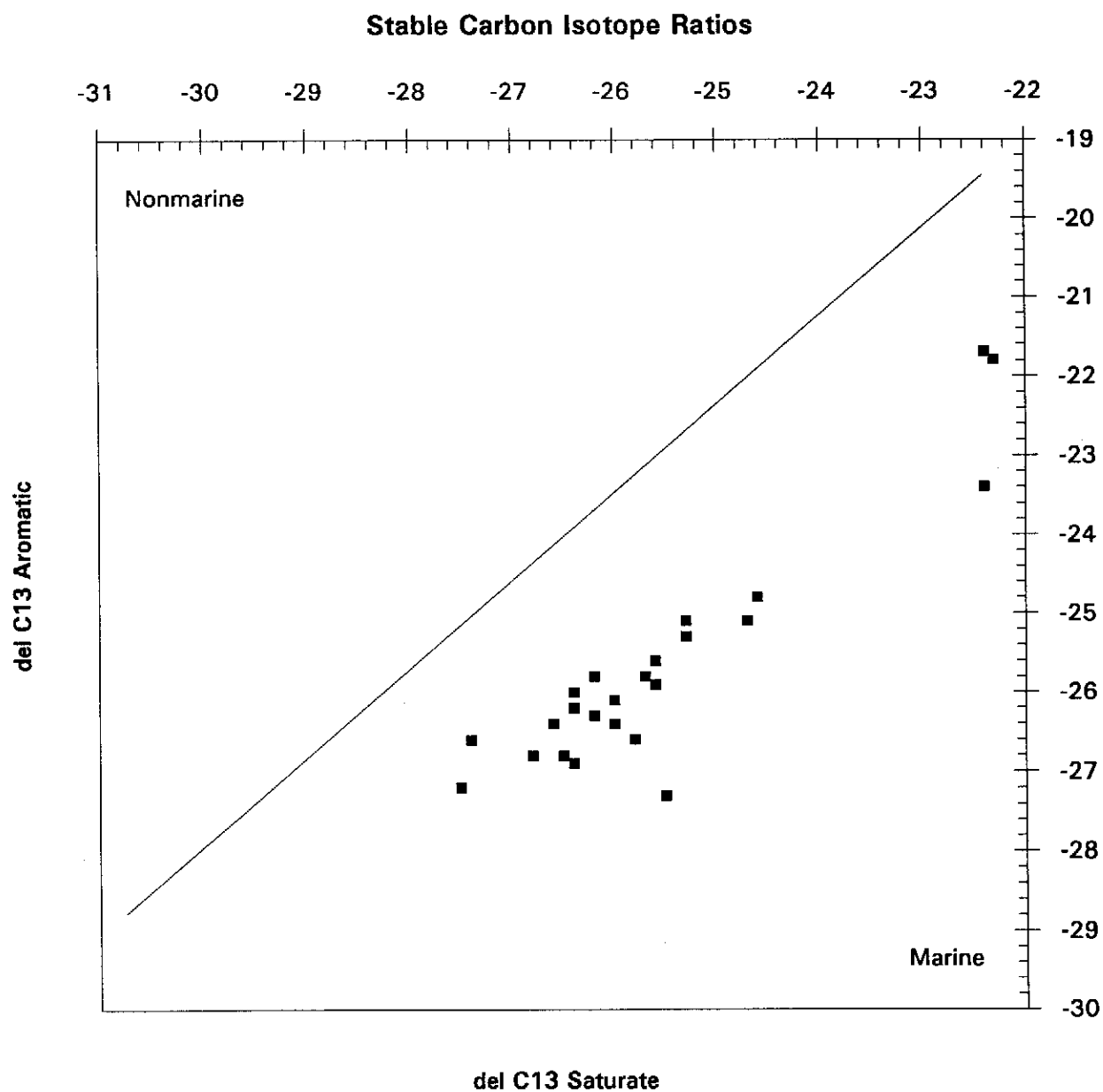
Figure 8. Crossplot of Stable Carbon Isotope Ratios (del C13 Aromatic Fraction vs. del C13 Saturate Fraction), Tanner, Carbon Canyon, Awatubi, and Walcott Members, Nankoweap Canyon and Carbon Canyon Areas.

Formation was at 8490 ft, top of Precambrian redbeds (Sixtymile Formation ?) was at 8703 ft and top of possible Chuar shales was at 9000 ft. A total of 309 ft of Precambrian sediments were encountered.

The Burnett Oil No. 1-36 Kaibab State well (36-43s-3w, Kane Co., Utah) reached a total depth of 5365 ft in possible Chuar Group shales. The top of the Tapeats Formation was at 4637 ft, top of the Precambrian Sixtymile Formation was at 4790 ft, and the possible top of the Chuar Group Shales was at 5350 ft. Samples are available from the International Sample Library at Midland in Midland, Texas. A total of 575 ft of Precambrian sediments was encountered.

The Shields Exploration No. 12-24 Federal well (24-41n-1w, Coconino Co., Arizona) reached a total depth of 5700 ft in the Precambrian Chuar Group. A letter from Jay Shields in the well files of the Arizona Geological Survey records the presence of Chuaria circularis in the conventional core from 4970 to 5000 ft. Seven-inch casing was set at 2958 ft and a production test was conducted from 2958 to 3183 ft in the Mississippian Redwall Formation. It is estimated that the top of the Tapeats Formation in this well occurs at about 4712 ft and the top of the Precambrian Sixtymile Formation occurs at about 4865 ft by correlation with the Burnett well. The total Precambrian sediment thickness encountered in this well is estimated at 835 ft.

Three of the 7 or 8 wells shown on maps of the Utah Geological and Mineral Survey (1990, p. 18) and Palacas (1992, Figure 5-4; 1997, p. 133, Figure 4) as penetrating Chuar or equivalent did not do so as far as can be determined. The maps do not identify the wells so well identity remains uncertain. The well in the southwest corner of Emery Co., Utah, appears to be the Mountain Fuel Supply No. 1A Last Chance well (18-26s-7e), which reached a total depth of 8518 ft in what we correlate as the Cambrian Muav Limestone.

The western-most of the 2 wells in south-central Emery Co., Utah, appears to be the Texaco No. 1 Temple Springs Unit well (14-25s-13e), which reached a total depth of 7314 ft in Precambrian schist. The top of the Tapeats Formation occurred at 6066 ft and the top of the schist occurred at 6210 ft based on the well cuttings sample log of American Stratigraphic Company of Calgary, Alberta, Canada. Their description is further supported by mica schist reported in core chips from 6363 to 6367 ft.

The eastern-most of the 2 wells in south-central Emery Co., Utah, appears to be the Texaco No. 2 Temple Springs Unit well (22-25s-14e), which reached a total depth of 7010 ft in Precambrian metamorphics. The top of the Tapeats Formation is at 6857 ft and the top of the Precambrian metamorphics is at 6884 ft based on the sample log of American Stratigraphic Company.

Depositional and Preservational Basin Geometry

Since our stable carbon isotope data (del C13 Saturate vs. del C13 Aromatic plot)

support a marine depositional environment for the plotted shale members of the Chuar Group (Tanner, Carbon Canyon, Awatubi, and Walcott Members), these deposits may well have been widely deposited on the Proterozoic shelf. It is possible that the Chuar Group of the Grand Canyon area, the Precambrian sediments in the 4 wells noted above, the Big Cottonwood Formation of the Salt Lake City area, and the Red Pine Shale of the Uinta Mountain Group in the Uinta Mountain area, were all deposited on one contiguous broad shallow shelf or a series of estuaries fringing this shelf. This is supported by the similar paleontological microbiotas reported by Bloeser and others (1977), Hoffman (1977), Vidal and Knoll (1983), Vidal and Ford (1985), and Vidal (1986).

As discussed by Sears (1990), 3 episodes of structural deformation affected the Grand Canyon Supergroup in the Late Precambrian: igneous intrusion, followed by crustal contraction, followed by crustal extension. The last episode, crustal extension, resulted in the formation of a series of northwest-southeast trending half graben bounded on the east by down-to-the west, west dipping normal faults, which flatten with depth. As the half-graben formed, the down-thrown block slipped down the fault plane and rotated the down-thrown beds. Following the extension, erosion peneplaned the Grand Canyon Supergroup, which resulted in the angular unconformity at the base of the Tapeats, which is called the "Great Unconformity" in the Grand Canyon area (Elston, 1989). The Tapeats was deposited on a generally level eroded Precambrian plain, which was, however, interrupted by ridges of Shinumo Quartzite with relief of up to 600 or 800 ft. There are areas where the Tapeats thins or pinches out across these paleo-hills (Middleton and Elliot, 1990, p. 86, 88 and 98; Sears, 1990, p. 79). The Chuar Group is preserved against the bounding fault at the eastern edge of these half graben where Tapeats lies on Chuar Group, but moving westwardly in a given graben, the Tapeats lies progressively on older Nankoweap and Unkar Group and finally on still older Vishnu Complex metamorphics (Sears, 1990, p. 74).

What is not clear is the form and extent of basins which may preserve Chuar Group source rocks in the subsurface. Is southern Utah and northern Arizona underlain by a single Chuar basin such as proposed by Rauzi (1990), Utah Geological and Mineral Survey (1990), and Palacas (1992; 1997) or are there a series of subbasins instead? Are Chuar or Chuar equivalent source rocks preserved in a series of half graben as suggested by Sears (1990) or are they preserved only in Precambrian intracratonic rifts such as the Uinta trough, Grand Canyon trough, and Beltian embayment as proposed by Marshak and van der Pluijm (1997)? According to Marshak and van der Pluijm (1997, Figure 19.10.2) there are relatively few Precambrian intracratonic rifts, numbering only about 13 in the entire United States. If Marshak and van der Pluijm's view is correct, large areas of Utah and Arizona may not be underlain by Chuar equivalents. The presence of apparent Chuar sediments in the 4 wells described above, however, suggests that Precambrian sediments are definitely present in portions of southern Utah and northern Arizona away from the Chuar Group outcrops in the Grand Canyon.

The present work suggests that only the uppermost Chuar Group constitutes

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significant source rock, including the 887 ft Walcott Member and the uppermost 165 to 390 ft of the Awatubi Member. This implies that where the "Great Unconformity" has erosionally removed this upper portion of the Chuar Group, significant source potential will be absent. If the structural pattern seen in the Grand Canyon is widespread due to widespread Proterozoic rifting (Sears, 1990) then this uppermost Chuar Group may be widely preserved on the eastern edges of these half graben.

Conclusions

(1)   The measured thickness of the Walcott Member is 887 ft, intermediate between that of previous authors. The measured thickness of the Awatubi Member is 855 ft in the Nankoweap Canyon area, somewhat less than that of previous authors. The thickness of the Carbon Butte Member varied from 247 ft in the Carbon Butte area to only 157 ft in the Nankoweap Canyon area. The thickness of the Carbon Canyon Member was 1060 ft, somewhat thinner than that of previous authors. Measured thicknesses of other units were compatible with previous reports (Table 1).

(2)   The modified van Krevelen diagram is not definitive as to kerogen type, apparently due to a fairly high maturity (0.5% Ro or higher) resulting in the clustering of points in the southwest corner of the diagram (Figure 4).

(3)   A Productivity Index (or Transformation Ratio) of less than 0.3 for all points except 1, indicates a maturity of immature or oil window and that hydrocarbons are indigenous to the source rocks analyzed (Figure 5).

(4)   The cross plot of Reactive Carbon Index vs. Productivity Index indicates Chuar points plot in the gas prone and uncertain area (Figure 5).

(5)   Organic petrology by DGSI indicated unstructured kerogen (lipids) makes up most of the organic matter in all of the samples. Minor amounts of vitrinite-like organic matter and solid bitumen occur as minor constituents amounting to at most 15% of the total organic fraction, but generally being present as traces. Vitrinite-like particles are either elongate or round and are both likely algal in origin. Solid bitumen occurs a pore filling or lining.

(6)   DGSI concluded that the solid organic matter had little or no fluorescence, which is consistent with the unstructured kerogens (lipids) which occur in the massive or massive to micritized stage.

(7)   DGSI noted that the TAI on the kerogen was uniformly 3 (condensate and wet gas of

DGSI; late oil of Peters and Cassa, 1994) or 3 to 3+ (condensate and wet gas to dry gas of DGSI; late oil (to postmature?) of Peters and Cassa, 1994) except for 1 sample.

(8)   This study does not support previous suggestions that the entire Chuar Group constitutes potential hydrocarbon source rocks. Only the 887 ft Walcott Member and the upper 165 to 390 ft of the Awatubi Member consistently have a TOC content of fair or better. This is about 60% of the total thickness of these 2 members. In the Galeros Formation, a total of 192 ft or 6% of the total thickness of the Tanner, Jupiter, and Carbon Canyon Members have a TOC content of fair or better. This 192 ft of the Galeros Formation may serve as secondary, relatively minor, potential source rocks in the study area. In other areas, these Galeros units could be significant source rocks if they improve in thickness or organic richness.

(9)   It is the maturity of the Walcott Member and the upper 165 to 390 ft of the Awatubi Member which is critical to sourcing potential reservoirs of the Tapeats and the Sixtymile Formations. In the Nankoweap Canyon area, the maturity gradient of these 2 intervals ranges from immature at the top to late oil at the base of the organically rich Awatubi. In the Carbon Canyon area, the maturity gradient of these 2 intervals is entirely immature. Deeper and/or longer burial in areas away from the Grand Canyon would be expected to result in a higher maturity for these potential Walcott and Awatubi Member source rocks.

(10)   The maturity gradient of the Nankoweap Canyon area appears to be higher than that of the Carbon Canyon area. Four explanations are proposed. Two explanations, (a) and (d) below assume the maturity gradient differences in the 2 areas are artificial rather than real. The other 2 explanations, (b) and (c) below, assume the maturity gradient differences are real. The 4 explanation are as follows:

(a)   The average Walcott maturity of 433 °C, which is 5 °C higher than the average Awatubi maturity of 428 °C in the Nankoweap Canyon area, may be skewing the Awatubi and total gradient (best fit line) toward artificially higher values. The average Awatubi maturity of 427 °C in the Carbon Canyon area is only 1 °C different than the average Awatubi maturity of 428 °C in the Nankoweap Canyon area. It is unclear why the average maturity of the Walcott is higher than the average maturity of the Awatubi in the Nankoweap Canyon area.

(b)   The higher maturity gradient of the Nankoweap Canyon area than the Carbon Canyon area may be a result of deeper and/or longer burial of the former area during the very long (230 million years) Late Precambrian extensional tectonic event (Grand Canyon disturbance) and erosion associated with the "Great Unconformity" or the later late Mesozoic to early Cenozoic Laramide orogeny.

(c)   The higher maturity gradient of the Nankoweap Canyon area than the Carbon Canyon area may be a result of higher heat flow in the former area during any of the 3 periods of volcanism and plutonism during the Cretaceous-Paleocene, Miocene, or Pliocene-Quaternary Periods/Epochs.

(d)   The discrepancy of the Galeros Formation portion of the maturity gradient curves for the 2 areas may not be real, being due to the margin of measurement error (error bars) around the few actual Galeros Formation data points.

(11)   The minor potential source rocks (192 ft total) of the Carbon Canyon, Jupiter, and Tanner Members have a Tmax maturity gradient ranging from the condensate and wet gas to dry gas windows in the Nankoweap Canyon area and ranging from the late oil to dry gas windows in the Carbon Canyon area.

(12)   DGSI noted that in the current sample set the correlations between Ro and Tmax was not strong. To investigate this a comparison was made between Tmax maturity and maturity suggested by the organic petrologic indicators (Table 4 and Figure 6). The organic petrologic maturity indicators compared to Tmax included: (1a) VRE converted from measured bitumen Ro using Landis and Castano's calibration chart; (1b) measured mean bitumen reflectance [Ro-(B)]; (1c) measured mean vitrinite-like reflectance [Ro-(O)]; (3) TAI converted to maturity zones using the delimiting values of DGSI; (4) TAI converted to maturity zones using the delimiting values of Peters and Cassa (1994) and Wapples (1980); and (5) extinction of sporinite and alginate fluorescence indicating an Ro of 1.20 or greater. For each sample locality a whole rock sample and a macerated kerogen concentrate sample were studied. In 22 of the 31 samples (71%) Tmax maturity was lower than all of the organic petrologic maturity indicators. This discrepancy appears to be most pronounced for the more immature samples. Four possible explanations are proposed as follows:

(a)   The true maturity of the samples, especially the more immature samples, may be higher than that indicated by the Tmax maturity. In other words, the organic petrologic maturity is correct and Tmax is wrong.

(b)   The Tmax maturity is correct and weathering or other causes have produced an apparent increase in the maturity of the organic petrologic indicators (Ro, TAI, and fluorescence). Moderate to strong iron oxide alteration, a known cause of elevated TAI values, was noted by DGSI in a number of whole rock samples.

(c)   Both organic petrologic maturity and measured Tmax values may be correct. Since maturation is a function of both time and temperature, the extreme age of the Chuar source rocks, 235 million years older than the usual Phanerozoic source rocks

(543 million years or younger), may have resulted in the higher effective maturity indicated by the organic petrology than normally expected at these Tmax temperatures.

(d)   The simple Proterozoic life forms may have unusual geochemical maturation pathways.

(13)   Based on the organic petrologic maturity indicators, in the Nankoweap Canyon area, most of the Walcott Member samples are in the peak oil to condensate/wet gas windows, and most of the Awatubi Member samples (all of which are from the upper organically rich section) are in the peak oil to condensate/wet gas windows, and most of the Carbon Canyon Member samples are in the condensate/wet gas window. Based on the organic petrologic indicators, in the Carbon Canyon area, most of the Awatubi Member samples (all of which area from the upper organically rich section) are in the immature to condensate/wet gas windows, and most of the Carbon Canyon Member samples in the late oil to condensate/wet gas windows, and the Tanner sample ranged from late oil to dry gas windows.

(14)   The Carbon Butte Sandstone shows distinct evidence of having been deposited under the influence of tidal forces and thereby having a shallow marine origin. Opposing crossbedding (north and south) indicates reversing currents and locally well developed sigmoidal crossbedding is characteristically produced by bedform migration under unequal reversing flow. Symmetric (wave) ripple marks in the upper part of the unit support a shallow water interpretation. The presence of multiple channels in the lower part, combined with mud chip conglomerates, argue for a setting in which tidal channels cut into associated muddy deposits. The thickness and laterally extensive distribution of the unit suggests deposition in a very large estuary or a tidal seaway.

(15)   The entire Tapeats Sandstone has been interpreted as a transgressive shallow marine deposit (Mckee, 1945), but the exposures in Nankoweap and Carbon Canyons appear largely to be of a nonmarine origin, particularly near the base. The uniformity of cross-bedding dip directions (toward the west), the lack of segregation of pebbles and sand typical of wave winnowing, and the lack of vertical trends indicative of shoreline sand successions or meandering streams argues for deposition in a fluvial braid plain environment. There is no question that elsewhere in the Canyon, the Tapeats contains trace fossils indicative of a marine setting (as at the confluence of the Colorado and Little Colorado Rivers), but these typically lie in the upper, "transitional" part of the section (McKee, 1945). We accept the Tapeats transgression postulated by McKee (1945), but feel that the initial Cambrian deposition, at least locally, began on a fluvial braid plain, as opposed to an offshore marine environment, as he envisioned. Hereford (1977) and Middleton and Hereford (1981) also

interpreted the Tapeats to consist of basal fluvial facies overlain by a variety of nearshore marine facies in north-central Arizona.

(16)   Thirty shale samples from the Tanner, Carbon Canyon, Awatubi, and Walcott Members were analyzed for compositional data (saturate hydrocarbons, aromatic hydrocarbons, resins, and asphaltenes) and for stable carbon isotope ratios. On a plot of the del C13 aromatic on the vertical axis vs. del C13 saturates on the horizontal axis (Figure 8), all 30 samples plot in the southeast diagonal half suggesting marine deposition for all 4 members.

(17)   Three wells in Utah (Tidewater No. 1 Kaibab Gulch Unit; Rangeland No. 1 Judd Hollow; and Burnett No. 1-36 Kaibab State) and 1 well in Arizona (Shields No. 12-24 Federal) penetrated Precambrian sediments. The penetrated Precambrian sediment thickness ranged from 309 to 1140 ft. None of these reached metamorphic or igneous basement to fully penetrate the Precambrian sedimentary section. Three of the wells in Emery County, Utah, reported to have penetrated Precambrian sediments (Chuar equivalents) in previous studies, are not believed to have penetrated any Precambrian sediments.

(18)   Marine deposition of the Tanner, Carbon Canyon, Awatubi, and Walcott Members imply the possibility that depositionally the Chuar Group, the Big Cottonwood Formation of the Salt Lake City area, and the Red Pine Shale of the Uinta Mountain Group in the Uinta Mountains may either have been contiguous or deposited in contemporaneous but separate marine embayments as suggested by previous authors.

(19)   The geometry of the preservational Precambrian basins after the very long Late Precambrian extensional tectonic event (Grand Canyon disturbance) and erosion (Great Unconformity) is unclear. Possibilities range from a single regional Chuar equivalent basin, a series of semi-regional subbasins, a series of half graben as seen in Grand Canyon outcrops, or only rare local Precambrian intracratonic rifts. The presence of Precambrian sediments in 4 wells in southern Utah and northern Arizona confirm Chuar equivalents do exist in the Utah-Arizona subsurface.

(20)   Where the Great (sub-Tapeats Formation) Unconformity has removed the upper Chuar Group (Walcott Member and upper organically rich Awatubi Member), significant source potential will be absent. If the structural pattern seen in the Grand Canyon with upper Chuar Group preserved in half graben is widespread due to widespread Proterozoic rifting, then this uppermost Chuar Group may be widely preserved on the fault-bounded edge of these rotated half graben.

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Appendix 1a. Analytical Data, Source Rock Analyses

Formation/ Member	Sample No.	Height	TOC (wt%)	HI	OI	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	PI	Tmax calc	RCI (%)	S2/S3	Ro eq. (%)
Nankoweap Canyon Area													
Sixtymile Fm	S7*	6189'	0.03										
	S6	6149'	0.06										
	S5	6119'	0.05										
	S4	6089'	0.05										
	S3	6059'	0.05										
	S2	6029'	0.04										
	S1	6000'	0.06										
Walcott Mbr	W41	5997'	3.23	76	49	0.14	2.44	1.58	0.05	425	7.99	1.54	1.30
	W40	5973'	2.70	34	37	0.16	0.93	1.01	0.15	427	1.04	0.92	
	W39	5948'	3.15	44	50	0.13	1.40	1.57	0.08	427	4.86	0.89	1.03
	W38	5924'	2.10	132	30	0.43	2.77	0.64	0.13	431	15.24	4.33	
	W37	5899'	1.47	49	40	0.22	0.72	0.59	0.23	423	6.39	1.22	
	W36	5874'	1.10	19	56	0.07	0.21	0.62	0.25	427	2.55	0.34	
	W35	5850'	1.10	0	76	0.02	0.00	0.84	1.00		0.18	0.00	
	W34	5825'	1.23	41	47	0.07	0.50	0.58	0.12	425	4.63	0.86	
	W33	5801'	3.63	67	32	0.39	2.43	1.15	0.14	429	7.77	2.11	
	W32	5776'	4.64	150	26	1.74	6.96	1.21	0.20	425	18.75	5.75	
	W30	5727'	4.55	102	38	0.38	4.66	1.71	0.08	431	11.08	2.73	
	W26	5628'	2.45	122	31	0.70	2.99	0.75	0.19	423	15.06	3.99	
	W23	5592'	0.07										
	W19	5506'	0.29										
	W18	5485'	1.64	95	41	0.41	1.55	0.67	0.21		11.95	2.31	
	W17	5456'	8.29	153	10	1.70	12.71	0.87	0.12	440	17.38	14.61	1.02
	W16	5432'	1.67	42	20	0.11	0.70	0.34	0.14	429	4.85	2.06	
	W15	5407'	2.72	168	17	1.18	4.56	0.47	0.21	431	21.10	9.70	
	W14	5395'	1.14	33	46	0.15	0.38	0.53	0.28		4.65	0.72	
	W13	5385'	1.09	175	17	0.56	1.91	0.19	0.23		22.66	10.05	
	W12	5358'	1.30	97	38	0.48	1.26	0.49	0.28		13.38	2.57	
	W11	5333'	0.76										
	W10	5309'	1.60	126	30	0.58	2.01	0.48	0.22	429	16.19	4.19	
	W09	5284'	0.79	8	103	0.03	0.06	0.81	0.33		1.14	0.07	
	W08	5260'	1.31	19	60	0.06	0.25	0.79	0.19		2.37	0.32	
	W07	5235'	0.51	12	106	0.01	0.06	0.54	0.14		1.37	0.11	
	W06	5210'	1.00	14	67	0.03	0.14	0.67	0.18		1.70	0.21	
	W05	5186'	2.31	94	32	0.09	2.17	0.75	0.04	429	9.78	2.89	1.13
	W04	5184'	0.09										
	W03	5161'	1.23	33	37	0.09	0.40	0.45	0.18		3.98	0.89	
	W02	5137'	2.53	162	14	0.46	4.11	0.35	0.10	437	18.06	11.74	
	W01	5124'	0.07										
Awatubi Mbr	A28	5097'	1.44	52	44	0.06	0.75	0.64	0.07		5.63	1.17	
	A27	5067'	0.26										
	A26	5037'	1.55	35	30	0.03	0.55	0.46	0.05	431	3.74	1.20	0.89
	A25.5	5012'	1.64	49	48	0.07	0.81	0.78	0.08	427	5.37	1.04	0.96
	A25	5007'	1.22	8	57	0.03	0.10	0.70	0.23		1.07	0.14	
	A24	4977'	0.69										
	A23	4947'	0.56										
	A22	4917'	0.16										
	A21	4857'	0.50										
	A20	4827'	0.36										
	A19	4797'	0.15										
	A18	4767'	0.09										
	A17	4737'	0.12										
	A16	4707'	0.24										
	A15	4677'	0.06										

Appendix 1a. Analytical Data, Source Rock Analyses (continued)

Formation/ Member	Sample No.	Height	TOC (wt%)	HI	OI	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	PI	Tmax calc	RCI (%)	S2/S3	Ro eq. (%)
Nankoweap Canyon Area													
Awatubi Mbr	A14	4647'	0.62										
	A13	4617'	0.20										
	A12	4587'	0.04										
	A11	4557'	0.66	21	42	0.02	0.14	0.28	0.13	440	2.42	0.50	
	A10.5	4542'	0.56	7	57	0.01	0.04	0.32	0.20		0.89	0.13	
	A10	4527'	0.03										
	A09	4497'	0.04										
	A08	4467'	0.07										
	A07	4437'	0.04										
	A06	4407'	0.02										
	A05	4377'	0.61	28	33	0.02	0.17	0.20	0.11	440	3.11	0.85	
	A04.5	4365'	0.53										
	A04	4347'	0.03										
	A03	4317'	0.37										
	A02	4287'	0.12										
	A01	4257'	0.02										
Carb Butte Mbr	040	4250'	0.03										
	036	4220'	0.02										
Duppa Mbr	030	3821'	0.02										
	029	3791'	0.04										
	028	3761'	0.04										
	027	3731'	0.12										
	026	3701'	0.21										
	025	3671'	0.03										
	024	3641'	0.03										
	023	3611'	0.02										
	022	3581'	0.12										
	021	3551'	0.02										
C Canyon Mbr	020	3521'	0.38										
	019	3491'	0.42										
	018	3461'	0.03										
	017	3431'	0.06										
	016	3401'	0.09										
	015	3371'	0.34										
	014	3341'	0.20										
	013	3311'	0.05										
	012	3286'	0.58										
	011	3281'	0.04										
	009	3251'	0.06										
	008	3221'	0.03										
	007	3191'	0.24										
	006	3161'	0.08										
	005	3131'	0.03										
	004	3101'	3.20	27	26	0.02	0.86	0.83	0.02	475	2.75	1.04	1.61
	CC1	~3101'	2.67	45	15	0.05	1.21	0.41	0.04	482		2.95	
	003	3071'	0.03										
	002	3041'	0.01										
	001	3011'	0.65										
Carbon Canyon Area													
Awatubi Mbr	SA19	5193'	0.43										
	SA20	5183'	3.78	281	30	0.72	10.59	1.14	0.06	427	29.92	9.29	
	SA18	5163'	3.25	242	34	0.45	7.87	1.11	0.05	429	25.60	7.09	

Appendix 1a. Analytical Data, Source Rock Analyses (continued)

Formation/ Member	Sample No.	Height	TOC (wt%)	HI	OI	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	PI	Tmax calc	RCI (%)	S2/S3	Ro eq. (%)
Carbon Canyon Area													
Awatubi Mbr	SA17	5133'	1.19	61	50	0.07	0.72	0.59	0.09	427	6.64	1.22	
	SA16	5103'	0.84	4	77	0.02	0.03	0.65			0.60	0.05	
	SA15	5073'	0.05										
	SA14	5043'	0.81	14	35	0.01	0.11	0.28	0.08		1.48	0.39	
	SA13	5013'	0.94	93	27	0.14	0.87	0.25	0.14	427	10.74	3.48	
	SA12	4983'	1.30	108	21	0.14	1.40	0.27	0.09	429	11.85	5.19	
	SA11	4953'	0.56	27	25	0.04	0.15	0.14	0.21		3.39	1.07	
	SA10	4928'	0.87	100	23	0.10	0.87	0.20	0.10	433	11.15	4.35	
	SA09	4923'	0.55	42	51	0.04	0.23	0.28	0.15		4.91	0.82	
	SA08	4903'	0.76	84	18	0.05	0.64	0.14	0.07		9.08	4.57	
	SA07	4893'	0.29										
	SA06	4863'	0.04										
	SA05	4833'	0.08										
	SA04	4803'	0.06										
	SA03	4773'	0.09										
	SA02	4743'	0.20										
	SA01	4713'	0.05										
	SAX7	4623'	0.03										
	SAX6	4588'	0.14										
	SAX5	4558'	0.05										
	SAX4	4528'	0.02										
	SAX3	4498'	0.07										
	SAX2	4468'	0.12										
	SAX1*	4441'	0.03										
Duppa Mbr	SD16	4171'	0.04										
	SD15	4141'	0.01										
	SD14	4111'	0.12										
	SD13	4081'	0.02										
	SD12	4051'	0.03										
	SD11	4021'	0.02										
	SD10	3901'	0.02										
	SD09	3871'	0.03										
	SD08	3841'	0.02										
	SD07	3811'	0.05										
	SD06	3781'	0.06										
	SD05	3721'	0.04										
	SD04	3691'	0.08										
	SD03	3661'	0.05										
	SD02	3631'	0.02										
	SD01	3571'	0.23										
C Canyon Mbr	SCC53	3541'	0.02										
	SCC52	3511'	0.04										
	SCC51	3481'	0.17										
	SCC50	3451'	1.27	31	57	0.02	0.39	0.72	0.05	450	3.23	0.54	
	SCC49	3421'	0.26										
	SCC48	3391'	0.02										
	SCC47	3361'	0.14										
	SCC46	3331'	0.23										
	SCCX1	3321'	2.64	77	20	0.56	2.03	0.52	0.22	444	9.81	3.90	
	SCC45	3301'	0.03										
	SCC44	3271'	0.03										
	SCC43	3241'	0.08										
	SCC42	3211'	0.05										
	SCC41	3181'	0.14										

Appendix 1a. Analytical Data, Source Rock Analyses (continued)

Formation/ Member	Sample No.	Height	TOC (wt%)	HI	OI	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	PI	Tmax calc	RCI (%)	S2/S3	Ro eq. (%)
Carbon Canyon Area													
C Canyon Mbr	SCC40	3151'	0.15										
	SCC39	3121'	0.05										
	SCC38	3091'	0.05										
	SCC37	3061'	0.03										
	SCC36	3031'	0.43										
	SCC35.5	3016'	0.72										
	SCC35	3001'	0.02										
	SCC34	2971'	0.03										
	SCC33	2941'	0.02										
	SCC32.5	2931'	0.04										
	SCC32	2911'	0.03										
	SCC31	2881'	0.05										
	SCC30	2851'	0.01										
	SCC29	2821'	0.03										
	SCC28	2791'	0.37										
	SCC27	2761'	0.04										
	SCC26	2731'	0.03										
	SCC25	2701'	0.09										
	SCC24	2671'	0.02										
	SCC23	2641'	0.01										
	SCC22	2611'	0.02										
	SCC21	2581'	0.03										
	SCC20	2551'	0.03										
	SCC19	2521'	0.04										
	SCC18	2491'	0.02										
Jupiter Mbr	SCC17	2461'	0.04										
	SCC16	2431'	0.03										
	SCC15	2401'	0.07										
	SCC14	2361'	0.08										
	SCC13	2331'	0.03										
	SCC12	2301'	0.06										
	SCC11	2271'	0.05										
	SCC10	2241'	0.05										
	SCC09	2211'	0.28										
	SCC08	2181'	0.09										
	SCC07	2151'	0.02										
	SCC06	2121'	0.24										
	SCC05	2091'	0.32										
	SCC04	2061'	0.03										
	SCC03	2031'	0.04										
	SCC02	2001'	0.04										
	SCC01	1971'	0.40										
	SJ32	1941'	0.02										
	SJ31	1911'	0.69	3	71	0.03	0.02	0.49	0.60		0.72	0.04	
	SJ30	1881'	0.08										
	SJ29	1851'	0.46										
	SJ28	1821'	0.02										
	SJ27	1791'	0.03										
	SJ26	1761'	0.02										
	SJ25	1731'	0.04										
	SJ24	1701'	0.02										
	SJ23	1671'	0.02										
	SJ22	1641'	0.02										
	SJ21	1611'	0.23										
	SJ20	1581'	0.12										

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Appendix 1a. Analytical Data, Source Rock Analyses (continued)

Formation/ Member	Sample No.	Height	TOC (wt%)	HI	OI	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	PI	Tmax calc	RCI (%)	S2/S3	Ro eq. (%)
Carbon Canyon Area													
Jupiter Mbr	SJ19	1551'	0.58										
	SJ18	1521'	0.23										
	SJ17	1491'	0.15										
	SJ16	1461'	0.04										
	SJ15	1431'	0.04										
	SJ14	1401'	0.04										
	SJ13	1371'	0.18										
	SJ12	1341'	0.03										
	SJ11	1311'	0.08										
	SJ10	1281'	0.16										
	SJ09	1251'	0.06										
	SJ08	1221'	0.06										
	SJ07	1161'	0.10										
	SJ06	1131'	0.07										
	SJ05	1101'	0.27										
	SJ04	1071'	0.24										
	SJ03	1041'	0.24										
	SJ02	1011'	0.04										
	SJ01	973'	0.18										
	SJX3*	956'	0.07										
	SJX2	951'	0.86	0		0.02	0	5.73	1.00			0.00	
	SJX1*	947'	0.07										
Tanner Mbr	ST22	936'	0.22										
	ST21	933'	0.85	12	65	0.03	0.10	0.55	0.23		1.53	0.18	
	ST20	886'	0.03										
	ST19	856'	0.16										
	ST18	826'	0.12										
	ST17	806'	0.18										
	ST16	766'	0.36										
	ST15	736'	0.21										
	ST14	706'	0.81										
	ST13	686'	0.21										
	ST12	676'	0.17										
	ST11	646'	0.42										
	ST10	616'	0.14										
	ST09	586'	0.15										
	ST08.5	566'	0.18										
	ST08	556'	0.14										
	ST07	526'	0.10										
	ST06	496'	0.18										
	ST05	466'	0.10										
	ST04	440'	1.41	16	22	0.00	0.23	0.31	0.00		1.63	0.74	
	ST03	438'	1.21										
	ST01	436'	0.02										

* Also analyzed for Reservoir Rock Properties in Appendix 1b.

Appendix 1b. Analytical Data, Reservoir Rock Properties

Formation / Member	Sample No.	Height	Permeability Kair (md)	Porosity (Helium) (%)	Grain Density (gm/cc)	Notes
NANKOWEAP CANYON AREA						
Tapeats Fm	T8	6394'	11.8	10.1	2.66	
	T7	6364'	169	12.6	2.66	
	T6	6334'	46.9	16.7	2.65	
	T5	6304'	42.1	10.2	2.65	
	T4	6274'	16.3	12.5	2.66	
	T3	6244'	8.11	11.8	2.66	
	T2	6214'	9.59	12.6	2.72	
	T1	6184'	0.40	6.2	2.70	
Sixtymile Fm	S7	6184'	770	18.3	2.66	
Walcott Mbr	W28	5678'	0.03	1.3	2.86	
	W27	5653'	0.56	2.3	2.87	
	W25	5604'	0.02	1.9	2.85	
	W24	5601'	0.03	4.3	2.85	
Carbon Butte Mbr	38	4230'	0.39	13.1	2.65	
	35	4190'	0.09	3.4	2.69	
	34	4160'	0.06	2.3	2.74	2 samples
	34	4160'	7.37	11.5	2.65	
	32	4130'	3.83	7.9	2.65	
	31	4100'	19.3	11.7	2.66	
Carbon Canyon Mbr	10	3271'	0.14	6.0	2.87	
Tanner Mbr	T2	401'	0.80	8.5	3.66	
	T1	373'	0.01	1.6	2.86	
Nankoweap Fm	N12	367'	0.20	4.2	2.70	
	N11	330'	0.52	4.2	2.65	
	N10	300'	0.28	6.1	2.65	
	N08	250'	0.05	4.0	2.67	
	N07	210'	0.40	5.3	2.67	
	N06	180'	0.02	1.3	2.66	
	N04	120'	36.4	14.6	2.71	2 bags
	N03	60'	0.12	8.5	2.67	
	N02	30'	0.04	3.7	2.67	
	N01	13'	12.7	12.0	2.69	
CARBON CANYON AREA						
Tapeats Fm	STP1	5390'	0.07	5.0	2.72	
	STP2	5380'	0.17	7.4	2.66	
	STP3	5361'	3.84	11.1	2.69	
	STP4	5355'	0.03	5.3	2.73	
	STP5	5347'	1.82	11.6	2.66	
Awatubi Mbr	SAX1	4441'	0.02	0.3	2.84	
Carbon Butte Mbr	SCB7	4416'	0.34	6.7	2.65	
	SCB6	4381'	0.53	6.3	2.65	
	SCB5	4356'	0.29	8.9	2.66	
	SCB4	4336'	0.49	3.0	2.65	
	SCB2	4226'	13.4	12.4	2.67	
	SCB1	4194'	0.39	6.9	2.67	
Carbon Canyon Mbr	SCC21.8	2607'	0.10	12.5	2.87	
Jupiter Mbr	SJX3	956'	0.08	3.9	2.86	
	SJX1	947'	0.04	2.7	2.83	

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Appendix 2a: Field Notes for Plate 1
CARBON CANYON AREA, CAPE SOLITUDE, COCONINO CO., ARIZONA, 7.5' TOPOGRAPHIC MAP

NOTE: All samples from Carbon Canyon Area (southern area) are designated by "S" as a sample number prefix to avoid confusion with the Nankoweap Canyon Area samples. Terminology of individual field groups is retained.

STRATIGRAPHIC SECTION, TAPEATS SANDSTONE, CARBON CANYON AREA, Measured October 10, 1996, by J.A. Moser. Section along trail from Colorado River up Carbon Canyon, along trail or hiking path. Section begins in Carbon Canyon hiking path about 2150' N80W from the intersection of Carbon Creek and the Colorado River, and ends 2400' N70W of the same intersection. Described and sampled section is incomplete. McKee, 1945, p. 142, described 300' of Tapeats section, about a mile to the south, east of Lava Canyon, 4 miles south of the little Colorado River.

TAPEATS FORMATION (300'?)

-- STAP* (300') (5643')	*ESTIMATE OF FULL SECTION FROM MCKEE, 1945, P. 142
-- STAP* (209') (5552')	
-- STAP1 (47.5') (5390.5')	15' above salt/alkali-saturated sandstone.
-- STAP2 (37.5') (5380.5')	5' above salt/alkali-saturated sandstone.
-- STAP*	*(32.5-47.5') (5375.5-90.5') Tapeats ss without salt/alkali precipitaion on face.
-- STAP3 (18.5') (5361.5')	Near base of salt/alkali-saturated sandstone. About 6' above green shale at base.
-- STAP*	*(12.5-32.5') (5355.5-75.5') Saline/alkaline water evaporating from formation face and precipitating salt/alkali.
-- STAP4	(12.0-12.5') (5355.0-55.5') Aquatard. Green micaceous shale. Possible base Tapeats, but probably not. Contains impressions from underlying pebbles.
-- STAP5 (04.0') (5347')	8' below green shale, probably basal Tapeats Sandstone.
-- STAP* (0-12') (5343-55')	*Tapeats Sandstone.

STRATIGRAPHIC SECTION, PART OF AWATUBI MEMBER, KWAGUNT FORMATION, CARBON CANYON AREA, Measured October 9, 1996, by B.H. Wiley, D.A. Cook, and L.C. Kuo. Section begins 4950' N25.5W of Carbon Butte peak.

NOTE: The SA section is measured on the north face of a very deep, steep canyon below the south side of Galeros Promontory. It is estimated that 1000 to 1500' of unmeasured Awatubi section lies below the following measured portion of the Awatubi. No Carbon Butte Member of the Kwagunt Formation was seen from above to lie downsection to the west on the north face of the steep canyon, despite it being mapped there by Ford and Breed, 1973. Thus no base of the Awatubi Member was seen or established, though a search in the bottom of the canyon may reveal it is present. Measurement of this portion of the Awatubi began (Sample SA01) on a resistive ledge of indurated grey siltstone.

WALCOTT MEMBER, KWAGUNT FORMATION (Est. ± 50')

-- SW* (0630') (5343')	*NOTE: Estimate 30 to 50' of Walcott above the Awatubi, capped by Tapeats, based on float of flaky dolomite of the Walcott Member found at the 480' level of the Awatubi.
-- SW* (0602') (5315')	
-- SW* (0580') (5293')	

AWATUBI MEMBER, KWAGUNT FORMATION (771'+)

		580' SA section + 191' SAX section = 771' total Awatubi Member
-- SA*	GAP (± 100')	*NOTE: Estimate an additional 100' to the base of the Walcott Member (flaky dolomite). This uppermost Awatubi and Walcott forms an extremely steep slope, and for this reason was not measured.
-- SA19	(0480') (5193')	Black shale, thin bedded.
-- SA20	(0470') (5183')	Black shale.
-- SA18	(0450') (5163')	Thin bedded carbonaceous, extremely black shale, with elemental sulphur on bedding planes.
-- SA17	(0420') (5133')	Thin bedded, carbonaceous shale with elemental sulphur on bedding planes.
-- SA16	(0390') (5103')	Grey shale, sulphur weathering.
-- SA15	(0360') (5073')	Light grey massive shale with sulphur weathering.
-- SA14	(0330') (5043')	Dark grey laminated shale, white laminations.
-- SA13	(0300') (5013')	Thinly laminated grey and dark-grey shale, abundant sulphur stain.
-- SA12	(0270') (4983')	Thinly bedded black shale with yellow sulphur weathering.
-- SA11	(0240') (4953')	Thinly laminated light and dark grey shale with yellow sulphur odor and stain (Odor present since first black shale at 180').
-- SA10	(0215') (4928')	Thin bedded dark grey-black shale.
-- SA09	(0210') (4923')	Grey mudstone to shale with white banding (laminations) and yellowish-brown weathering.
-- SA08	(0190') (4903')	Very black, thin to medium bedded shale.

-- SA07 (0180') (4893')   Black , thin-bedded shale.
-- SA06 (0150') (4863')   Blue-grey shale, medium bedded.
-- SA05 (0120') (4833')   Blocky grey shale.
-- SA04 (0090') (4803')   Severely weathered brown-grey shale, blocky with dark brown-black weathering.
-- SA03 (0060') (4773')   Dark bluish-green shale, thinly bedded, severely weathered red (hematite-like).
-- SA02 (0030') (4743')   Grey shale with orange to brown weathering, thin to medium bedded.
-- SA01 (0000') (4713')   Indurated grey siltstone, forming a resistive (to weathering) ledge.

Strike N33W, dip 5° NE

GAP of 84' (THIS STUDY) TO 359' (FORD AND BREED, 1973)

NOTE: Ford and Breed (1973) measured 1130' of Awatubi section. This study measured 855' of Awatubi in the Nankoweap Canyon Area and 771' of Awatubi in the Carbon Canyon Area (191' of SAX section above the basal stromatolite bed, and 580' of SA section (480' measured + 100' estimated) below the base of the Walcott flaky dolomite). A minimum gap between the basal SAX section and the capping SA section is estimated to be 84' (855'-771') compared to the Nankoweap Canyon Area or 359' (1130'-771') compared to Ford and Breed, 1973. It was estimated that as much as 1000' to 1500' of measured Awatubi might lie below the measured SA section. Maximum Awatubi thickness in the Carbon Canyon Area could be 2080' (1500' + 580').

STRATIGRAPHIC SECTION, LOWER AWATUBI MEMBER, KWAGUNT FORMATION, CARBON CANYON AREA, Measured October 10, 1996, by E.H. Clifton, B.H. Wiley, L.C. Kuo, and S.L. Rauzi. The SAX section begins 1500' S16.5W of Carbon Butte peak (excluding Random Carbon Canyon Member Sample - see SCC45.5). [ehc--Section begun at base of algal limestone/dolomite about 400 m south of Carbon Butte (top bed in October 9 section of Clifton, Moser, and Rauzi). SAX section is continuation of October 9 section measured by Clifton, Moser, and Rauzi].

SECTION ABOVE IN-SITU AWATUBI MEMBER IS COVERED BY LANDSLIDE MASS COMPOSING CARBON BUTTE.

-- SAX* (0191') (4629')   *Ss ledge, top of exposed, in-situ Awatubi Member.
                             (188-191') = 3' of indurated siliceous, very fine grained sandstone.
-- SAX7 (0188') (4626')   brn mds (brown mudstone)
-- SAX* (0180') (4618')   *covered, no sample
                             mostly covered
-- SAX* (0165') (4603')   *2' fg massive ss
-- SAX6 (0150') (4588')   gry sh (medium grey shale)
                             mostly covered
-- SAX5 (0120') (4558')   light brn mds, weathers red (Brown to red mds. Originally light brown, weathering to dark red)
                             brn, red yellow sh, thin slts beds
-- SAX4 (0090') (4528')   light brn mds (Light brown mudstone (shale))
                             red/brn/gry sh, slts beds w/mudcracks
-- SAX3 (0060') (4498')   brn-gry mds (Brown-grey mudstone (shale), weathering brown)
                             olive sh, thin slts beds
-- SAX2 (0030') (4468')   olive sh (Grey-brown shale. Awatubi Member, Kwagunt Formation)
                             olive sh, ls/dol at base
-- SAX* (0009') (4447')   *9' = Top basal Awatubi Member stromatolite bed. (Total thickness stromatolite bed = 9')
-- SAX1 (0003') (4441')   ls/dol (Finely crystalline dolomite in basal Awatubi Member stromatolite bed)
-- SAX* (0000') (4438')   *base of stromatolitic ls/dol (basal stromatolite bed)

Dip on Carbon Butte Member, Kwagunt Formation sandstone located 45' stratigraphically below the base of the Awatubi Member, Kwagunt Formation basal stromatolite bed :   *Strike N30W, dip 15° NE.*

STRATIGRAPHIC SECTION, CARBON CANYON, DUPPA, AND CARBON BUTTE MEMBERS, CARBON CANYON AREA,
Measured October 9, 1996, by E.H. Clifton, J.A. Moser, and S.L. Rauzi. Section begun at base of lowest algal limestone/dolomite on south bank of Carbon Canyon (top bed in October 8 section measured by Clifton, Moser, and Rauzi). Section is continuation of October 8 section; sample numbers carried on from October 8, although SCC19 probably actually is the second sample in the Carbon Canyon Member.

CARBON BUTTE MEMBER, KWAGUNT FORMATION (247')

		Section ended about 400 m south of Carbon Butte
-- SCB*	(1947') (4438')	*base of algal ls/dol
-- SCB7	(1925') (4416')	ss, reservoir sample
-- SCB*	(1920') (4411')	*covered, no sample
-- SCB6	(1890') (4381')	ss, reservoir sample
		interbedded red mds and thin ss layers
-- SCB5	(1865') (4356')	ss, reservoir sample
-- SCB*	(1860') (4351')	*covered, no sample
-- SCB4	(1845') (4336')	rippled ss, reservoir sample
-- SCB*	(1830') (4321')	*covered, no sample
-- SCB*	(1815') (4300')	*1' fg indurated ss
-- SCB*	(1800') (4291')	*covered, no sample
-- SCB*	(1770') (4261')	*covered, no sample
		mudcracks, wavy bedded ss, poor exposure
-- SCB*	(1740') (4231')	*top of thick resistant ss
		red resistant ss
-- SCB3	(1735') (4226')	ss, reservoir sample (missing 4226, SCB3)
		red resistant ss
-- SCB2	(1735') (4226')	ss, reservoir sample
		red resistant ss
-- SCB1	(1703') (4194')	ss, reservoir sample
		red resistant ss
-- SD*	(1700') (4191')	*Ss, base of Carbon Butte Fm

beds dip: 15° toward 010°

BASE CARBON BUTTE MEMBER

DUPPA MEMBER, GALEROS FORMATION (640')

		gry mds, flaggy ss with rhythmic bedding
-- SD16	(1680') (4171')	gry mds
		gry mds, fg ss w/x-bedding towards E
-- SD15	(1650') (4141')	red mds
		gry mds/slts
-- SD14	(1620') (4111')	gry mds
		gry mds/slts
-- SD13	(1590') (4081')	gry mds
		gry mds/slts
-- SD12	(1560') (4051')	gry-grn mds
		gry mds, thin ss beds
-- SD11	(1530') (4021')	blk mds
-- SD*	(1500') (3991')	*covered, no sample
		covered
-- SD*	(1470') (3961')	*covered, no sample
		covered
-- SD*	(1440') (3931')	*covered, no sample
		covered
-- SD10	(1410') (3901')	grn mds
		dk mds
-- SD09	(1380') (3871')	gry mds
		gry mds
-- SD08	(1350') (3841')	red mds
		gry sh, some slts
-- SD07	(1320') (3811')	gry sh

```
                                       gry sh
-- SD06  (1290') (3781')    gry sh
                                       gry sh, covered
-- SD*   (1260') (3751')    *covered, no sample
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                                                                                               beds dip: 20° toward 030°

```
                            60% red mds, 30% ls/dol (10' set of beds, stromatolitic?)
-- SD05  (1230') (3721')    red mds
                                       red and grn mds, thin ls/dol beds
-- SD04  (1200') (3691')    red mds
                                       red and minor grn mds, mostly covered
-- SD03  (1170') (3661')    red mds
                                       red and grn mds, mostly covered
-- SD*   (1140') (3631')    *covered, no sample
                                       covered
-- SD02  (1110') (3601')    red mds
                                       red sh minor ls/dol
-- SD01  (1080') (3571')    gry fissile sh
```
                                       BASE DUPPA MEMBER

                            red beds change to grn/gry 20' upsection

CARBON CANYON MEMBER, GALEROS FORMATION (1060')

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-- SCC*     (1060') (3551')                      *top of highest thick ls/dol (top of Carbon Canyon Fm)
-- SCC53.0  (1050') (3541')       gry sh
                                  80% grn mds, 10% red mds, 10% ls/dol
-- SCC52.0  (1020') (3511')       red mds                            beds dip: 10° toward 020°
                                  red sh, ls/dol, poorly exposed
-- SCC51.0  (0990') (3481')       grn sh
                                  80% red mds, bright grn mds layer
-- SCC50.0  (0960') (3451')       dk gry sh
                                  dk sh, prominent ls/dol, poor exposure
-- SCC49.0  (0930') (3421')       dk gry sh                          beds dip: 10° toward 360°
-- SCC48.0  (0900') (3391')       gry-grn mds/sh
                                  80% grn mds, 20% red mds
-- SCC47.0  (0870') (3361')       gry mds
                                  60% grn mds, 40% red mds
```

follow prominent ls/dol bed to Middle Fork of Carbon Creek   *beds dip: 8° toward 020°*

```
-- SCC46.0  (0840') (3331')       stomatolitic ls/dol, prominent bed
                                  40% gry mds, 60% ls/dol
-- SCCX-1   (0830') (3321')       "Random Carbon Canyon Sample" - 4' dark black shale.  Approximately 830',
                                  equivalent to SCC 45.5.
-- SCC45.0  (0810') (3301')       olive mds
                                  gry grn mds, poorly exposed
-- SCC44.0  (0780') (3271')       dk gry, red-weathering mds
                                  covered, grn mds, few ls/dol beds
-- SCC43.0  (0750') (3241')       dk gry mds
                                  60% grn mds, 25% red mds, 15% ls/dol
-- SCC42.0  (0720') (3211')       grn mds
                                  60% red mds, 40% grn mds
-- SCC41.0  (0690') (3181')       dk laminated ls/dol                beds dip: 10° toward 330°
                                  red and grn mds
-- SCC40.0  (0660') (3151')       dk gry mds
                                  red and grn mds, mostly covered
-- SCC39.0  (0630') (3121')       gry ls/dol
                                  30% grn mds, 40% red mds, 30% ls/dol
-- SCC38.0  (0600') (3091')       grn mds
                                  90% grn mds, 10% ls/dol, much algal struct, mudcracks common
```

-- SCC37.0 (0570') (3061')   grn mds
                                     60% grn sh, 30% red mds, 10% ls/dol
-- SCC36.0 (0540') (3031')   red mds
                                     60% dk grn sh, 30% red mds, 10% ls/dol
-- SCC35.5 (0510.5') (3001.5')   6' blk-dk grn sh, fissile
-- SCC35.0 (0510') (3001')   gry sh
                                     60% red mds, 20% grn mds, 10% ls/dol, 10% ss
-- SCC34.0 (0480') (2971')   grn mds
-- SCC33.5 (0450') (2941')   tuff? (ash bed?) not sampled for source
                                     90% red mds, 10% ls/dol
-- SCC33.0 (0450') (2941')   mottled red/grn mds
-- SCC32.6 (0440') (2931')   2' blk algal ls/dol   *beds dip: 10° toward 345°*
                                     60% red mds, 20% grn mds, 20% ls/dol. 8' bed of clean ss
                                     ledge-former, continue in floor and north side of West Fork, Carbon Creek
-- SCC32.0 (0420') (2911')   dk gry ls/dol
                                     90% red mds, 10% ls/dol
-- SCC31.0 (0390') (2881')   gry-grn mds
                                     55% red mds, 15% ls/dol, 30% gry mds?   *beds dip: 10° toward 350°*
-- SCC30.0 (0360') (2851')   red mds

follow resistant marly sh at 345' (2836') to south side of West Fork of Carbon Creek   *beds dip: 10° toward 345°*

-- SCC29.0 (0330') (2821')   sandy grn mds
                                     70% ls/dol, 30% gry mds, mostly at top
-- SCC28.0 (0300') (2791')   brn marl
                                     80% red mds, 20% grn mds
-- SCC27.0 (0270') (2761')   sandy red mds
                                     60% gry sh, 40% red mds, prominent tan ls/dol bed
-- SCC26.0 (0240') (2731')   gry sh, reddish
                                     95% gry sh. 5% algal ls/dol
-- SCC25.0 (0210') (2701')   sandy gry mds
                                     mostly covered gry mds, ls/dol
-- SCC24.0 (0180') (2671')   ls/dol
                                     80% gry marly mds, 10% algal ls/dol, 10% red mds
-- SCC23.0 (0150') (2641')   calcar poorly sorted ss
                                     80% gry marly mds sh, 5% ls/dol, 5% tight fg ss
-- SCC22.0 (0120') (2611')   ls/dol
-- SCC21.8 (0116') (2607')   vuggy ls/dol (reservoir sample - not sampled for source)
                                     60% gry sh, 40% ls/dol beds
-- SCC21.0 (0090') (2581')   ls/dol
                                     40% gry sh, 60% ls/dol beds
-- SCC20.0 (0060') (2551')   marly gry sh
                                     60% gry sh, 40% ls/dol
-- SCC19.0 (0030') (2521')   ls/dol
                                     95% ls/dol   *beds dip: 40° toward 282°*
-- SCC18.0 (0000') (2491')   sampled 10/8/96, probable base of Carbon Canyon Fm

STRATIGRAPHIC SECTION, JUPITER MEMBER, GALEROS FORMATION, LAVA CANYON AND CARBON CANYON AREAS,
Measured October 8, 1996, by E.H. Clifton, J.A. Moser, and S.L. Rauzi. Section begun at top of stromatolitic dolomite at waterfall in Lava Canyon.

JUPITER MEMBER, GALEROS FORMATION (1545')
                                     1510' + 35' measured below waterfall = 1545' total Jupiter Member
-- SCC18 (1510') (2491')   = algal limestone (true base of Carbon Canyon Mbr)
-- SJ*   (1500') (2481') =SCC*   *no sample
                                     mostly covered
-- SJ49 (1480') (2461') =SCC17   gry sh

	mostly covered	
-- SJ48 (1450') (2431') =SCC16	brn mds	
-- SJ47 (1420') (2401') =SCC15	gry sh	
	95% gry sh, 5% carbonate beds	
-- SJ46 (1380') (2361') =SCC14	grn mds	
	gry sh, mostly covered	
-- SJ45 (1350') (2331') =SCC13	gry mds	
	gry sh with a prominent set of thickening-up ls/dol beds	
-- SJ44 (1320') (2301') =SCC12	gry slts	
	gry sh	
-- SJ43 (1290') (2271') =SCC11	gry silty sh	
	gry sh	
-- SJ42 (1260') (2241') =SCC10	gry sh	
	90% gry sh, 10% carbonate beds	
-- SJ41 (1230') (2211') =SCC09	gry-grn mds	
	80% red mds, 20% carbonate beds	
-- SJ40 (1200') (2181') =SCC08	red mds	
	95% red mds	
-- SJ39 (1170') (2151') =SCC07	red mds	
	80% red sh, 10% grn mds, 10% ls/dol beds	
-- SJ38 (1140') (2121') =SCC06	gry mds	
	40% red mds, 30% gry mds, 30% ls/dol beds	
-- SJ37 (1110') (2091') =SCC05	gry mds	
	70% variegated red/grn mds, 30% resistant carbonate beds	
-- SJ36 (1080') (2061') =SCC04	red mds	
	95% red mds, one thin fg ss	
-- SJ35 (1050') (2031') =SCC03	reddish/gry sh	
	90% gry sh, 10% carbonate beds	
-- SJ34 (1020') (2001') =SCC02	gry-grn sh	
	95% gry sh, 5% carbonate beds	
-- SJ33 (0990') (1971') =SCC01	gry sh	
	gry sh, resistant marly sh and carbonates	
-- SJ* (0970') (1951')	*mapped top of Jupiter, section above is probably still Jupiter	
	(carbonate beds are thin, show little, if any, algal structure)	
-- SJ32 (0960') (1941')	gry/red sh	
	gry sh, red mds at top	
-- SJ31 (0930') (1911')	blk sh j	
	80% gry sh, 20% slts	
-- SJ30 (0900') (1881')	gry sh	*beds dip: 25° towards 360°*
	80% gry sh, 20% slts	
-- SJ29 (0870') (1851')	gry sh	
	50% red mds, 50% gry sh w/ slts beds	
-- SJ28 (0840') (1821')	red sh/slts	
	50% red mds, 40% gry sh, 10% slts	
-- SJ27 (0810') (1791')	red mds	
	90% red mds	
-- SJ26 (0780') (1761')	red mds	
	90% red mds/slts	
-- SJ25 (0750') (1731')	red mds	*beds dip: 48° towards 018°*
	80% red mds, 20% gry sh	
-- SJ24 (0720') (1701')	gry mds	*beds dip: 40° towards 020°*
	90% red mds, 10% gry sh	
-- SJ23 (0690') (1671')	red mds	*beds dip: 38° towards 020°*
-- SJ22 (0660') (1641')	red mds	
	gry/brn sh	
-- SJ21 (0630') (1611')	fissile brn/dk gry sh	
	gry/brn sh	
-- SJ20 (0600') (1581')	gry sh	
	gry/brn sh	

-- SJ19 (0570') (1551')   gry sh
                           gry/brn sh, minor slts
-- SJ18 (0540') (1521')   gry/brn sh
                           gry/brn sh, some slts beds
-- SJ17 (0510') (1491')   brn sh/slts
                           color change to yellow, more slts
-- SJ16 (0480') (1461')   red mds
                           red mds
-- SJ15 (0450') (1431')   red mds
                           90% red mds, 8% grn sh, 2% slts
-- SJ14 (0420') (1401')   red mds
                           90% red mds, 8% grn sh, 2% slts
-- SJ13 (0390') (1371')   dk gry sh
                           90% red mds, 8% grn sh, 2% slts
-- SJ12 (0360') (1341')   red/gry sh   *beds dip: 38° towards 360°*
                           60% red mds, 30% gry sh, 10% slts
-- SJ11 (0330') (1311')   gry sh
-- SJ10 (0300') (1281')   gry mds (305')
                           80% red mds, 10% grn sh, 10% slts
-- SJ09 (0270') (1251')   red mds
                           fissile sh, slts, mostly covered
-- SJ08 (0240') (1221')   red mds   *beds dip: 35° towards 350°*
                           50% red mds, 30% slts, 20% gry mds
-- SJ*   (0210') (1191')   *covered, no sample
                           probably mostly gry sh
-- SJ07 (0180') (1161')   gry sh
                           90% gry sh/slts, 10% slts beds
-- SJ06 (0150') (1131')   gry sh
                           gry sh, thin beds of laminated slts
-- SJ05 (0120') (1101')   gry sh
                           gry sh
-- SJ04 (0090') (1071')   gry sh   *beds dip: 40° towards 015°*
                           90% gry sh, 10% red sh
-- SJ03 (0060') (1041')   blk sh
                           15% fissile gry sh, 85% red sh
-- SJ02 (0030') (1011')   reg/grn silic sh
                           70% gry sh, 30% carbonate beds
-- SJ*   (0000') (0981')   *no sample   *beds dip: 20° towards 350°*
-- SJ01 (--08') (0973')   dolomite, petroliferous

STRATIGRAPHIC SECTION, TANNER AND JUPITER MEMBERS, GALEROS FORMATION, CARBON CANYON AREA,
Measured October 8, 1996, by B.H. Wiley, D.A. Cook, L.C. Kuo. Section begins 13,650' S12E of Carbon Butte peak.

JUPITER MEMBER, GALEROS FORMATION (35')
-- SJ*   (035') (0981')   Total *estimated thickness of Jupiter Member stromatolitic limestone.
-- SJX3.0 (010') (0956')   Stromatolitic limestone.
-- SJX2.0 (005') (0951')   Dark grey to black limy shale. (Interbedded within Jupiter Member stromatolitic limestone).
-- SJX1.0 (1.5') (947.5') Jupiter Member, Galeros Formation. Stromatolitic limestone.

TANNER MEMBER, GALEROS FORMATION (574')
                           510' shale measured this study + 64' dolomite per Ford & Breed = 574' total Tanner Member
-- ST*   (0510') (0946') = *Top of Tanner Member, base of Jupiter Member stromatolitic limestone bed. Begin
                           renumbering Jupiter Member at 0' at the base of the stromatolitic limestone bed.
-- ST22.0 (0500') (0936') Grey shale mudstone with thin shale rip-up clasts. Tanner Member, Galeros Formation.
-- ST21.0 (0497') (0933') Very thin bedded chocolate brown-black shale.
-- ST20.0 (0450') (0886') Highly indurated green and purple siltstone, 2' thick. (5' of green and purple siltstone, less
                           indurated above the indurated unit at 450').

-- ST19.0 (0420') (0856')   Light grey shale, thin bedded, fairly resistive to weathering.
-- ST18.0 (0390') (0826')   Medium grey, blocky shale.
-- ST17.0 (0370') (0806')   Light grey shale at the base of salt leaching from beds. Salt leaching zone is 30' thick.
-- ST16.0 (0330') (0766')   Shale, medium grey.

OFFSET 2000' TO EAST, ON NORTH SIDE OF LAVA CREEK CANYON, WEST OF CHUAR LAVA HILL. DIP 26° NW.

-- ST15.0 (0300') (0736')   Medium grey shale, thin bedded.
-- ST14.0 (0270') (0706')   Black, thin bedded resistive (to weathering), shale. Brown weathering on bedding.
-- ST13.0 (0250') (0686')   Thin bedded dark grey shale, orange weathering.
-- ST12.0 (0240') (0676')   Thin bedded dark grey shale.
-- ST11.0 (0210') (0646')   Thin bedded grey shale.

Strike N10E, dip 23° SE. Note: Dave Cook got *strike N45W, dip 23° NE*.
OFFSET 2000' TO WEST, JUST EAST OF SOUTHERLY FORK OF LAVA CREEK.

-- ST10.0 (0180') (0616')   Thinly bedded dark grey shale.
-- ST09.0 (0150') (0586')   Very thinly bedded light grey and black shale. Brown shale on bedding surfaces.
-- ST08.5 (0130') (0566')   Medium grey shale.
-- ST08.0 (0120') (0556')   Thin bedded green-grey shale, red-brown weathering on bedding surfaces.
-- ST07.0 (0090') (0526')   Thinly bedded light grey shale.
-- ST06.0 (0060') (0496')   Thin bedded dark grey and brown shale, Tanner Member shale, Galeros Formation.
-- ST05.0 (0030') (0466')   Thin bedded greenish shale with hematite, Tanner Member shale, Galeros Formation.
-- ST04.0 (0004') (0440')   Blocky black shale, sulphurous.
-- ST03.0 (0002') (0438')   Flaky black shale, thinly bedded, sulphurous.
-- ST01.0 (0000') (0436')   Coarsely crystalline dolomite. Top of Tanner Member dolomite, Galeros Formation.

Strike N16E, dip 24° NW, on top of Tanner Member dolomite, Galeros Formation.

-- ST* (064') (436')   *NOTE: 64' of Tanner Member dolomite per Ford and Breed, 1973, Fig. 2.

-- SN* (372') (372')   *NOTE: Nankoweap Formation not measured in Carbon Canyon Area but 372' is estimated based on the 372' of Nankoweap Formation that was measured in the Nankoweap Canyon Area (Plate 2).

NANKOWEAP CANYON AREA, POINT IMPERIAL, COCONINO CO., ARIZONA, 7.5' TOPOGRAPHIC MAP

NOTE: Terminology of individual field groups is retained.

STRATIGRAPHIC SECTION, TAPEATS FORMATION, NANKOWEAP CANYON AREA, Measured October 6, 1996, by E.H. Clifton, J.A. Moser, and L.C. Kuo. Section begun at lowest exposed Tapeats about 500 m west of the Nankoweap trail / basal Tapeats crossing.

TAPEATS FORMATION (225')   NOTE: Tapeats disignated as "TP" in Figure 2 to distinguish from Tanner Member

T*	(225') (6409')	Top of the Tapeats	
T8	(210') (6394')	ss, mg	
			100% sandstone, few pebbles, Fe-cemented, highly indurated
T7	(180') (6364')	ss, few pebbles	
			100% pebbly sandstone, fewer and smaller pebbles.
T6	(150') (6334')	pebbly ss	
			100% pebbly sandstone, planar-tabular crossbeds to W.
T5	(120') (6304')	pebbly ss	
			100% pebbly sandstone, planar-tabular crossbeds to W.
T4	(090') (6274')	pebbly ss	

Section continued on Nankoweap trail

			100% pebbly sandstone, planar-tabular crossbeds to W.
T3	(060') (6244')	pebbly ss	
			100% pebbly sandstone, planar-tabular crossbeds to W. "pea gravel" beds <1'
T2*	(030') (6214')	pebbly ss	
			100% pebbly sandstone, planar-tabular crossbeds to W <2 m, pebbles <3 cm
T1*	(000') (6184')	pebbly ss	

STRATIGRAPHIC SECTION, WALCOTT MEMBER, KWAGUNT FORMATION, AND SIXTYMILE FORMATION, NANKOWEAP CANYON AREA, Measured October 5, 1996, by B.H. Wiley, D.A. Cook, and J.A. Moser. Section begins 1200' N22E of Nankoweap Butte. Section ends at top of Nankoweap Butte. NOTE: At the base of the Walcott section, beds strike N55W, dipping 35° SW due to a location on the NE limb of the syncline shown by Huntoon and others, 1996. The synclinal axis is crossed approximately at the top of the Walcott section (0° dip) and the basal Sixtymile section is on the SW limb of this syncline, with beds striking N10E, but now dipping 2-5° NW. The Walcott thicknesses were measured in the field assuming 35° SW dip for the entire section. The actual average dip for the section is probably close to 17.5° SW [= (0 + 35)°/2]. Therefore, thicknesses have been corrected to an average dip of 17.5° SW, from the 35° used in measuring in the field. The ground slope was determined to be 31° NE from the topographic map. Corrected thickness equals measured thickness times sin 48.5° divided by sin 66°. [The thicknesses listed below are: field measured, (corrected field measured), and (corrected cumulative)].

SIXTYMILE FORMATION (185')

-- S7.0	185' (0185') (6184')	Red sandstone with pink and tan brecciated clasts. Top of Nankoweap Butte	
-- S*	155' (0155') (6154')	*Chaotic breccia with shale clasts.	
-- S6.0	150' (0150') (6149')	Angular shale clast breccia, clasts of red and tan siltstone.	
-- S5.0	120' (0120') (6119')	Red siltstone with oval (cigar shaped) balls of tan siltstone.	
			Strike N12E, dip 10° NW
-- S4.0	090' (0090') (6089')	Purple siltstone.	
-- S3.0	060' (0060') (6059')	Purple and cream siltstone, thinly bedded.	
-- S2.0	030' (0030') (6029')	Red-purple siltstone, medium bedded, thin laminations of white and red-purple.	
-- S1.0	0.5' (00.5') (5999.5')	Tan, thin bedded siltstone, indurated.	
-- S*	0.0' (0000') (5999')	= *Base Sixtymile Formation	*Strike N10E, dip 2-5° NW*

WALCOTT MEMBER, KWAGUNT FORMATION (887')

-- W*	1082' (0887') (5999')	= *Top Walcott Member, Kwagunt Formation = Base Sixtymile Formation. Begin renumbering formation thickness for Sixtymile Formation at base Sixtymile Formation.	
-- W41	1080' (0885') (5997')	Black shale with red weathering on bedding planes.	
-- W40	1050' (0861') (5973')	Thin to moderately bedded, black shale with red weathering on bedding planes.	
-- W39	1020' (0836') (5948')	Black, thin to moderately bedded shale, red weathering.	

-- W38 0990' (0812') (5924')   75% black moderately bedded shale mixed with 25% red shale.
-- W37 0960' (0787') (5899')   Thin bedded black shale with red weathering on bedding planes.
-- W36 0930' (0762') (5874')   Red and black shale mixed.
-- W35 0900' (0738') (5850')   Thin bedded black shale.
-- W34 0870' (0713') (5825')   Black shale, very thinly bedded.
-- W33 0840' (0689') (5801')   Black shale, medium bedded.
-- W32 0810' (0664') (5776')   Black shale.
-- W31* 0780' (0639') (5751')   *Covered, no sample.
-- W30 0750' (0615') (5727')   Black shale, thin bedded.
-- W29* 0720' (0590') (5702')   *Covered, no sample.
-- W28 0690' (0566') (5678')   Grey, finely crystalline dolomite. (not sampled for source, possible reservoir sample). (541 - 589') (5653 - 5701') = Upper dolomite of the Double Dolomite. Karsted, faulted, brecciated dolomite with stylolites, and common vugs with pyrite crystals.
-- W27 0660' (0541') (5653')   Dark grey dolomite w/ white blebs. Basal part of upper dolomite of Double Dolomite. = Base of the upper dolomite of the Double Dolomite. (not sampled for source rock, possible reservoir sample).
-- W26 0630' (0516') (5628')   Black shale.
                                  At (494 - 541') (5606 - 5653') = Black shale.
-- W25 0600' (0492') (5604')   Very hard dolomite. Top of the Lower dolomite of the Double Dolomite. (not sampled for source rock, possible reservoir sample).
-- W24 0597' (0489') (5601')   Oolitic dolomite of the Lower dolomite of the Double Dolomite. (not sampled for source rock, possible reservoir sample). (482 - 494') (5594 - 5606') = Oolitic dolomite with stylolites (15' thick) of the lower dolomite of the Double Dolomite.
-- W23 0585' (0480') (5592')   Algal laminated dolomite with petroleum odor (3 samples). (478 - 482') (5590 - 5594') = Algal dolomite (5' thick) of the lower dolomite of the Double Dolomite. 583' (478') (5590') = Base of lower of two dolomites of Double Dolomite.
-- W22* 0570' (0467') (5579')   *Covered, no sample, probably shale.
-- W21* 0540' (0443') (5555')   *Covered, no sample, probably shale.
-- W20* 0510' (0418') (5530')   *Covered, no sample, probably shale.
-- W19 0480' (0394') (5506')   Limy grey dolomite with spherical objects.
-- W18 0455' (0373') (5485')   Black shale, moderately thick bedding, sulphide weathering.
-- W17 0420' (0344') (5456')   Black, carbonaceous, thinly bedded shale.
-- W16 0390' (0320') (5432')   Very thin bedded black shale, yellow sulphur-like weathering between bedding planes.
-- W15 0360' (0295') (5407')   Thin bedded black shale, indurated.
-- W14 0345' (0283') (5395')   Black pisolite.
-- W13 0330' (0271') (5383')   Medium bedded jet black shale. More indurated.
-- W12 0300' (0246') (5358')   Thin bedded black shale.
-- W11 0270' (0221') (5333')   Thin bedded black shale.
-- W10 0240' (0197') (5309')   Thinly bedded black shale, organic odor.
-- W09 0210' (0172') (5284')   Dark grey to black shale.
-- W08 0180' (0148') (5260')   Black shale.
-- W07 0150' (0123') (5235')   Black shale, blocky.
-- W06 0120' (0098') (5210')   Black shale.
-- W05 0090' (0074') (5186')   Black shale.
-- W04 0088' (0072') (5184')   White cherty pisolite. (70 - 72') (5182 - 5184') = White pisolite. Above and below = black shale.
-- W03 0060' (0049') (5161')   Black shale. (25 - 49') (5137 - 5161') = Black shale.
-- W02 0030' (0025') (5137')   Black, thin bedded shale, slight yellow (sulphur ?) stain.
-- W01 0015' (0012') (5124')   Flaky dolomite, algal. At (0 - 18') (5112 - 5130') = Flaky dolomite.
-- W*   0000' (0000') (5112')   *Base of "flaky dolomite" = base of Walcott Member, Kwagunt Formation.
                                  Strike N55W, dip 35° SW

STRATIGRAPHIC SECTION, AWATUBI MEMBER, KWAGUNT FORMATION, NANKOWEAP CANYON AREA, Measured
October 5, 1996, by E.H. Clifton, L.C. Kuo, and S.L. Rauzi. Section begun at base of stromatolitic dolomite about 1 km
north of Nankoweap Butte.

AWATUBI MEMBER, KWAGUNT FORMATION (855')

-- A29.0 (0855') (5112')	base of "flaky dolomite" (sample missing)	
	gry sh	
-- A28.0 (0840') (5097')	gry sh	
	gry sh	
-- A27.0 (0810') (5067')	blocky gry sh	
	gry sh	
-- A26.0 (0780') (5037')	gry sh	
	dk-gry sh	
-- A25.5 (0755') (5012')	dk-gry-bk sh w/yellow (sulphur?) matter on bedding planes	
-- A25.0 (0750') (5007')	fissile dk-gry sh	
	gry sh	
-- A24.0 (0720') (4977')	fissile dk-gry sh	
	gry sh	
-- A23.0 (0690') (4947')	gry sh	
	gry sh	
-- A22.0 (0660') (4917')	gry sh	
	gry sh	
-- A* (0630") (4887')	*covered, no sample	
	gry sh	
-- A21.0 (0600') (4857')	gry sh	
	gry sh	
-- A20.5 (0570') (4827')	gry sh, weathered	
	gry sh	
-- A19.0 (0540') (4797')	gry sh	
	gry sh	
-- A18.0 (0510') (4767')	gry sh	
-- A17.0 (0480') (4737')	gry sh	
	gry sh	
-- A16.0 (0450') (4707')	gry sh	
	gry sh	
-- A15.0 (0420') (4677')	gry sh	
	gry sh	
-- A14.0 (0390') (4647')	gry sh	
	gry sh, with a few lintic beds of sugary fg ss	
-- A13.0 (0360') (4617')	gry sh	*beds dip: 30° towards 195°*
	gry sh	
-- A12.0 (0330') (4587')	gry sh	
	gry sh	
-- A11.0 (0300') (4557')	dk gry sh	
-- A10.5 (0285') (4542')	blk/dk gry sh gry sh	
-- A10.0 (0270') (4527')	gry sh	
	gry sh	
-- A09.0 (0240') (4497')	gry, grn-red sh	*beds dip: 30° towards 195°*
	gry sh	
-- A08.0 (0210') (4467')	gry sh	
	gry sh	
-- A07.0 (0180') (4437')	gry sh	
	gry sh, mudcracks in float	
-- A06.0 (0150') (4407')	lt gry sh	
	gry sh	
-- A05.0 (0120') (4377')	gry sh	*beds dip: 30° towards 210°*

Section Continued on well-exposed slope about 700 m northeast of Nankoweap Butte, at approximately the 120' level

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-- A06.0  (0150') (4407')   gry sh
                                    90% gry sh, 10% maroon sh
-- A05.0  (0120') (4377')   gry sh
                                    80% gry sh, 20% maroon sh
-- A04.5  (0100') (4357')   dk gry sh, 3' thk
-- A04.0  (0090') (4347')   maroon sh
                                    50% gry sh, 50% maroon-weathering sh
-- A03.0  (0060') (4317')   gry sh
                                    60% gry sh, 40% maroon sh
-- A02.0  (0030') (4287')   gry sh
                                    80% gry sh, 90% dolomite (base stromatolite 9' thk = 4266')
-- A01.0  (0000') (4257')   dolomite                           beds dip: 30° towards 195°
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STRATIGRAPHIC SECTION, CARBON BUTTE MEMBER, KWAGUNT FORMATION, NANKOWEAP CANYON AREA, Measured
October, 5, 1996, by E.H. Clifton, B.H. Wiley, D.A. Cook, J.A. Moser, L.C. Kuo, and S.L. Rauzi. Section begins 3900'
N44W of Nankoweap Butte.

CARBON BUTTE MEMBER, KWAGUNT FORMATION (157')
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-- 041*  (0157') (4257')   = *Top Carbon Butte Member = Base Awatubi Member, = base stromatolite bed.
-- 040   (0150') (4250')   Red shale.
-- 039*  (0135') (4235')   Coarse sandstone, calcareous cemented. *Sample missing.
-- 038   (0130') (4230')   White, calcareous cemented, fine grain sandstone. = 2' above base of first white sandstone
                           above the Carbon Butte basal tight red sandstone.
                           (128 - 138') (4228 - 4238') = White sandstone.
                           (120 - 128') (4220 - 4228') = Red shale.
-- 037*  (0125') (4225')   *No sample 37 at 125' = drop.
-- 036   (0120') (4220')   Red, poorly sorted siltstone with fine to medium, red sand grains. (5' below base of first white
                           sandstone above Carbon Butte basal tight red sandstone).
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SAMPLES 36-40 FROM DRAW (STREAMBED) BETWEEN BUTTES OF SAMPLES 31-32 AND 34-35. THIS SECTION IS ALSO
ABOVE SAMPLES 4-30.

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-- 035   (0090') (4190')   Purplish and white banded (laminated) fine grain sandstone.
-- 034   (0060') (4160')   Red and white, laminated, fine grain sandstone.
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SAMPLES 34-35 FROM CREST OF NEXT BUTTE TO NORTHEAST.

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-- 033*                    *No sample 33, out of place, drop.
-- 032   (0030') (4130')   Pink, well cemented fine grain sandstone.
                           (0 - 30') (4100 - 4130') = Same as sample 32.
-- 031   (0000') (4100')   Base Carbon Butte Member, Kwagunt Formation. Thinly bedded red, fine grain sandstone, well
                           cemented. Tidally influenced with sigmoids and reversing cross-beds.
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STRATIGRAPHIC SECTION, CARBON CANYON AND DUPPA MEMBERS, GALEROS FORMATION, NANKOWEAP CANYON
AREA, Measured October 4, 1996, by E.H. Clifton, B.H. Wiley, D.A. Cook, J.A. Moser, L.C. Kuo, and S.L. Rauzi. Section
begun in Nankoweap Creek drainage about 5800' N26W of Nankoweap Butte.

Strike N30E, dip 24° SE

DUPPA MEMBER, GALEROS FORMATION (549')
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-- 0*  279' COVERED        (810 - 1089') (3821 - 4100') = *279' covered to base of Carbon Butte (sandstone) Member.
-- 030   (0810') (3821')   Red mudstone.
                           (780 - 810') (3791 - 3821') = Grey shale.
-- 029   (0780') (3791')   Limestone with sideritic pellets.
                           (756.5 - 757.5') (3767.5 - 3768.5') = I' limy siltstone, algal.
                           (755 - 756.5') (3766 - 3767.5" = 1 1/2' thin bedded shale and limy siltstone.
                           (753 - 755') (3764 - 3766') = 2' algal (?) limestone, sharp based, aphanitic and massive, hint
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		algal structure, some evidence of soft sediment deformation, nodules.
-- 028	(0750') (3761')	Dark red shale.
		(720 - 750') (3731 - 3761') = Alternating red and green siltstones.
-- 027	(0720') (3731')	Grey-green mudstone, weathers red.
		(690 - 720') (3701 - 3731') = As per sample 26.
-- 026	(0690') (3701')	Light grey, weathering to red, thinly bedded shale, with very thin black, shiny laminations.
-- 025	(0660') (3671')	Red shale.
		(630 - 660') (3641 - 3671') = Red shale.
-- 024	(0630') (3641')	Red shale.
		(600 - 630') (3611 - 3641') = Red shale.
-- 023	(0600') (3611')	Red shale.
		(570 - 600') (3581 - 3611') = Grey-green shale.
-- 022	(0570') (3581')	Gray-green shale.
		(540 - 570') (3551 - 3581') = Grey-green shale.
-- 0*	(0540') (3551')	*Base of Duppa Member.

CARBON CANYON MEMBER, GALEROS FORMATION (540'+)

-- 021	(0540') (3551')	Red shale/mudstone = top of Carbon Canyon Member = base of Duppa Member.
		(515') (3526') = Varved algal limestone. 3' limestone, 4' grey shale, repetitive interbedded sequence.
-- 020	(0510') (3521')	Dark grey shale.
		OFFSET
-- 019	(0480') (3491')	Greenish - grey shale.
-- 018	(0450') (3461')	Green and red shale.
		(420 - 450') (3431 - 3461') = 10% Green shale, 20% limestone, 70% red shale.
-- 017	(0420') (3431')	Grey-green shale.
		(390 - 420') (3401 - 3431') = Probably same as sample 16. Covered.
-- 016	(0390') (3401')	Grey-green shale.
		(360 - 390') (3371 - 3401') = Probably same as sample 15. Covered.
-- 015	(0360') (3371')	Grey-green shale.
		(330 - 360') (3341 - 3371') = 5% red shale, 10% limestone, 85% grey-green shale.
-- 014	(0330') (3341')	Dark grey shale.
		(300 - 330') (3311 - 3341') = 30% limestone, 10% black shale, 60% grey shale. (6' limestone with mudcracks & algal wavy stratification.)
-- 013	(0300') (3311')	Red siltstone.
-- 012	(0275') (3286')	Black shale.
		(270 - 300') (3281 - 3311') = 60% grey shale, 20% red shale, 10% limestone, 10% black shale.
-- 011	(0270') (3281')	Grey-green shale.
		(260 - 270') (3271 - 3281') = Grey-green shale.
-- 010*	(0260') (3271')	Porous (?) stromatolitic limestone. *(Reservoir sample).
		(240 - 260') (3251 - 3271') = Same as sample 9.
-- 009	(0240') (3251')	Marly limestone.
		(210 - 240') (3221 - 3251') = Slightly thicker bedded, 10' red shale and 10' grey shale alternating. Same percentage: 75% red shale, 15% grey-green shale, 10% limestone.
-- 008	(0210') (3221')	Red shale.
		(180 - 210') (3191 - 3221') = Same as interval 150 - 180'.
-- 007	(0180') (3191')	Stromatolitic limestone, 4 1/2 to 5' thick.
		(150 - 180') (3161 - 3191') = 75% red shale, 15% grey-green shale, 10% limestone.
-- 006	(0150') (3161')	Dark red shale.
		(120 - 150') (3131 - 3161') = 80% red shale, 10% grey-green shale, 10% limestone, cross bedded, pelleted, and sandy. The thick grey-green shale underlie the limestone. At (140-141') (3151-3152') is 1' of limestone for reservoir potential (?)
-- 005	(0120') (3131')	Dark brown-red shale.
		(90 - 120') (3101 - 3131') = 45% red shale, 45% grey-green shale, 10% limestone. From 90 to 95' = 5' limestone, overlain by 4' green shale (95 to 99'), overlain by 2' algal limestone.
-- 004	(0090') (3101')	Dark grey black shale.
		Offset 700' to Southwest

	At 3071 - 3096' (60 - 85') = Same as sample 3.
-- 003 (0060') (3071')	Red shale.
	At 3041 - 3071' (30 - 60') = Same as sample 2.
-- 002 (0030') (3041')	Red shale. Carbon Canyon Member.
	At 3011 - 3041' (0 - 30') = 90% red shale, 5% grey-green shale, 5% dolo. with wavy algal structure.
-- 001 (0000') (3011')	In Carbon Canyon Member. Dolo. / Ls. *Strike N10E, dip 32° SE*

-- CC1 *   *NOTE: Sample CC1, thin bedded black shale, is lower part of the measured portion of the Carbon Canyon Member in the Nankoweap Canyon Area. Its exact stratigraphic position is uncertain. It is possibly equivalent to sample 004 at 90' (3101').

BASE NOT ESTABLISHED

STRATIGRAPHIC SECTION, NANKOWEAP FORMATION AND TANNER MEMBER, GALEROS FORMATION, NANKOWEAP CANYON AREA, Measured October 6, 1996, by B.H. Wiley, D.A. Cook, and S.L. Rauzi. Section begins 7900' N18W of Nankoweap Butte.

TANNER MEMBER, GALEROS FORMATION (29 + ')
ADDITIONAL TANNER DOLOMITE CAPPED BY TANNER OR JUPITER SHALES CAPPED UNCONFORMABLY BY TAPEATS, NOT EXAMINED

Butte is capped by alluvium/colluvium. Walking down-slope and along bedding into the saddle to the north, we saw additional section of Tanner dolomite in the saddle, overlain by Tanner shale or Jupiter shale (not examined in time available), forming the slope to the north. This shale is capped unconformably by Tapeats Sandstone.

	Top of Tanner member dolomite as exposed on this butte.
-- T2 (29') (0401')	Same description as T1. From top of dolomite exposed on this butte.
-- T1 (01') (0373')	Dark grey, coarsely crystalline dolomite, sucrosic, with very thin algal (?) laminations replaced by chert. Weathers very dark brown. Fractured. Possible calcite veins.
-- T* (00') (0372')	= *Base of Tanner Member, begin renumbering at 0' at base of Tanner Member.

NANKOWEAP FORMATION (372')

| -- N* (0372') (0372') | = *Top of Nankoweap Formation = base of Tanner Member, Galeros Formation (dolomite). Begin renumbering stratigraphic thickness of Tanner Member at 0'. |
| -- N12 (0367') (0367') | Red sandstone, cross-bedded, ripple marks. |

OFFSET TO BUTTE TO WEST, ADD 12' MAKING TOP OF NANKOWEAP FORMATION AT 372'.

-- N* (0360') (0360')	= *Top bleached white sandstone.
	Strike N8E, dip 17° SW
-- N11 (0330') (0330')	Bleached white sandstone, massively crossbedded, well-sorted, well-rounded grains, fine to medium grained sandstone. Possibly eolian.
-- N10 (0300') (0300')	Bleached white sandstone with very well sorted, rounded grains. Well cemented. Bleached white sandstone is massively crossbedded with crossbed at approximately 45° to bedding planes. 300' = Contact of red quartzite and bleached white sandstone.
-- N09* (0270') (0270')	*Covered. No sample.
-- N08 (0250') (0250')	Rust - brown quartzite.
-- N07 (0210') (0210')	Tan buff quartzite or very well cemented fine grain sandstone.
-- N06 (0180') (0180')	Well cemented quartzite, grey, medium bedded.
-- N05* (0150') (0150')	*Covered, no sample, probably red siltstone.
-- N04 (0120') (0120')	Fine grained, well sorted, white sandstone with black grains (possibly dead oil?). Ripple marks.
-- N* (0090') (0090')	*(60 - 90') = Same as N03.
-- N03 (0060') (0060')	Interbedded white, purplish red, and white sandstone. Fine grained, indurated sandstone with ripple marks.
	(30 - 60') = Same as N02. Well indurated. Staining only on weathered surfaces. Unweathered surfaces are grey.

-- NO2   (0030') (0030')   Slightly coarser, well sorted, medium grained sandstone, thin bedded, quartz sandstone, white and red-brown layers, cross bedding and dark brown stain. Well cemented.
(0 - 30') = Same as NO1 with climbing ? ripple marks and low angle cross-bedding and slickensides.

-- NO1   (0013') (0013')   Nankoweap Formation. Apparently porous, medium bedded red sandstone, fine grained, well sorted, quartz sandstone with hematite or red cement with white.

Strike N50W, dip 18° NE

CARDENAS BASALT